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SAMPLE III – SC05

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Specific Contract N^{o}: SC05

SAMPLE III: Contribution to aircraft engine PM certification requirement and standard Fifth Specific Contract– Final Report

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Disclaimer

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Executive Summary

This report details the methods, results and conclusions of the project entitled "SAMPLE III: Contribution to aircraft engine PM certification requirement and standard". This project was funded via the European Aviation Safety Agency (EASA) under the Specific Contract N^{o}: **SC05** Implementing Framework Contract N^{o}: **EASA.2010.FC10**.

The work relative to the development of a non-volatile PM (nvPM) certification requirement had reached a point where:

- The nvPM Aerospace Recommended Practice (ARP) needed to be drafted based upon AIR6241 methodology, to meet regulatory timescales
- The EU/EASA nvPM system needed to be maintained and calibrated to AIR6241 compliance
- Inter-comparison data with an engine manufacturer system was required to assess nvPM measurement uncertainty and system operation robustness in harsh testing environments.
- Data needed to be gathered and analysed behind current production aircraft engines to support decisions to be made within ICAO/CAEP.

To meet the above requirements, the objectives of this specific contract include: Providing support to SAE E31 to draft nvPM ARP, maintain EU/EASA nvPM system to AIR6241 compliance, perform AIR6241 compliant measurement of non-volatile particulate matter at the exhaust of large-scale (>26.7 kN thrust) gas turbine aircraft engines, perform AIR6241 compliant inter-comparisons between EU/EASA and Rolls-Royce nvPM systems, perform analysis of nvPM data gathered during previous SAMPLE test campaigns, acquire and analyse additional engine PM data, all in support of the development of a robust 'ballot-ready' ARP which will subsequently enable a non-volatile particulate matter (nvPM) certification requirement. Assessing the validity of correcting the gathered nvPM data to predict accurate engine exit nvPM emissions.

Key results and recommendations from this study include:

1) Drafting of the SAE E31 nvPM ARP has started with significant progress made via a number of drafts throughout 2014

2) The SAE E31 nvPM ARP is currently on schedule for early 2015. The ARP's delivery date will depend upon proof of robust measurement and operational testing of the proposed nvPM system by all engine manufacturers.

3) Further nvPM engine and laboratory testing will be required post-ARP ballot if a reduction in nvPM measurement uncertainty is needed by ICAO/CAEP/WG3/PMTG.

4) An additional user operability section has been added to the draft ARP and provided in time to be used for other inter-comparison test campaigns such as the US VARIAnT study.

5) The particle line loss correction methodology has been trialled using an existing SAMPLEIII SC03 dataset with issues identified and communicated back to SAE E31.

6) The EU/EASA nvPM system was fully calibrated and maintained for the system inter-comparison testing during SAMPLEIII SC05 to AIR6241 compliance

7) Calibration of equipment is time intensive (taking up to 6 weeks in the case of the AVL APC) and scheduling this in accordance with engine testing was difficult.

8) Dedicated training for operational staff and clear system operating procedures are required to ensure smooth operation of an nvPM measurement system. Specific small engine test training and the writing of standard operating procedures and checklists for the EU/EASA nvPM system has been performed.

9) Maintenance of the equipment has been simplified by having a dedicated operational staff; along with the benefit of improved design changes, brought upon by specific testing issues.

10) The primary Dilution Factor should be monitored over time (multiple test campaigns), as part of routine maintenance, to determine when the diluter nozzle orifice needs cleaning, however it is perceived that the newly installed back-purge facility will reduce this requirement.

11) Long term drift should be monitored of all nvPM instrumentation to establish the confidence level. Further effort is needed to work with instrument manufacturer's to change internal practices and provide "as found" calibration prior to instrument service maintenance procedures, as a routine to provide better understanding of instrument drift.

12) The dilution check for the VPR (DF2) is an important part of the nvPM system operability. Up to 10 % variability is allowed with values of 8 % being observed, for the lowest PCRF setting of 100. Reducing this variability could reduce overall nvPM EI uncertainty.

13) Two AIR6241 compliant nvPM systems (RR and EU/EASA) were successfully installed, operated and tested back-to-back on a lean burn staged engine across a wide range of engine power conditions

14) Two AIR6241 compliant nvPM measurement analyser systems (RR and EU/EASA) were successfully installed, operated and tested back-to-back on an in-production rich burn engine at two power conditions.

15) The possibility of installing, and therefore performing, a full sampling system inter-comparison is facility dependent. This will have an impact on the possibility of performing this specific test type in the future. However, different types (as detailed in the report) of system inter-comparison tests are beneficial and advantageous to SAE E31 to further assess and minimise sources of nvPM measurement uncertainty.

16) For the lean burn staged engine two distinct nvPM regimes were observed: pilot only mode, similar to in-production rich burn; and the much lower emissions were observed at the staged mode, four orders of magnitude lower for number and three orders of magnitude lower for mass.

17) The lean burn staged engine results were similar to engine inlet ambient concentrations and also around the instruments' limit of detection.

18) For both mass and number the lean burn staged engine conditions produced instrument inlet concentrations which were lower than the AIR6241 instrument calibration levels (<10 µg/m^3; <1e3 P/cm^3) which increases the overall measurement uncertainty.

19) The inter-comparison of the nvPM systems (RR and EU/EASA) for Emissions Index number (EInum) for both the lean burn pilot only and the in-production rich burn engines, showed consistency with previous SAMPLE III SC02 and SC03 studies. Namely that the variability is within the E31 estimated ±25 % uncertainty. It should be noted that this study is the first time different number measurement instrumentation was compared and that the uncertainty has not increased.

20) The inter-comparison of the nvPM systems (RR and EU/EASA) for Emissions Index mass (EImass) for both the lean burn pilot only and the in-production rich burn engines, showed consistency with previous SAMPLE III SC02 and SC03 studies. Namely that the variability is within the E31 estimated ±25 % uncertainty.

21) Some measurements for both mass and number were close to the instrumentation level of detection. High variability (>±2 5%) was observed, which is consistent with previous studies.

22) It can be seen that absolute variability of EImass and EInum is dependent on the EImass and EInum data level.

23) Inter-comparison of the RR and EU/EASA nvPM analysers only showed that intra-system variability was reduced to ±6% and ±9% for EInumber and EImass respectively. This shows that the sampling source variability is around ±10 to 20 % which is consistent with SAMPLEIII SC02 findings.

24) A Limit of Quantification (LOQ) could be established using standard deviation and the PMTG acknowledged maximum uncertainty level (e.g. ±25 %). It is recommended that 2sigma deviation should be reported with nvPM data to help provide data for a possible LOQ calculation. Further statistical work is required to verify an LOQ limit, for example performing normality tests on individual data points as well as statistically testing repeated datasets.

25) Both nvPM systems were operability compliant to AIR6241, whilst they were operating sequentially.

26) The primary Dilution Factor of both systems was capable of operating within the prescribed AIR6241 range for the specific probe/rake setup utilised.

27) Any bias of the CO_2 analyser is an important component of the uncertainty, reducing this could improve particle measurement uncertainty.

28) In order to reduce EInum variability, there is potential to reduce the uncertainty in VPR dilution factor (DF2) by accounting for penetration differences at different dilution settings.

29) An assessment of adding an additional 0.9 m length to 4PTS (25 m) shows negligible impact to both mass and number nvPM instrumentation for both nvPM systems, in agreement with the UTRC line loss model.

30) SMPS and DMS size measurements on the lean burn pilot only engine were monomodal and agreed well after particle transport correction. With DGNs within 4 % average variance. Across all conditions DGNs were witnessed between 30 to 50 nm.

31) For the lean burn staged measurements both size instruments were close to their limit of detection.

32) Size measurements showed negligible impact of the additional 4PTS line length used in the in-production rich burn engine test.

33) Comparison between the MSS and LII showed good agreement with a small 7 % bias well within the expected uncertainty of calibration.

34) SC05 work on line loss corrections highlights the need to perform a full error analysis on the model, taking account of all uncertainties in the predicted line loss and measured data

35) It is vital that any line loss correction has reliable sampling system penetration and loss functions.

36) It is clear that the effects of the line loss increases with decreasing particle size.

37) There is a need to validate the VPR loss functions below 15 nm (where the function is an extrapolation and not fitted to data), as they are having a significant impact on the reported results.

38) Engine exit plane concentrations predicted by the Line Loss Correction Analysis (LLCA) for the EU/EASA and RR systems vary between ~54 % to 123 % for number and ~13 % to 4 5% for mass. Furthermore, physically non-realistic size distributions are sometimes produced. It needs to be understood whether these differences are within an acceptable experimental uncertainty or whether the LLCA does not represent the physical processes in the line.

39) For both the lean burn staged and Small helicopter engines, the LLCA predicted 5PTS distributions (mass and number) do not match the measured SMPS distributions with an assumed density of 1 g/cm^3, a sigma of 1.8 and an assumption of sphericity.

40) The SMPS always measures a larger diameter than predicted at the instruments. Consequently, the predicted exit plane total number using the SMPS data is lower than the LLCA model and the exit plane geometric mean diameter, (DGN) is larger.

41) The predicted mass from the SMPS assuming a density of 1 g/cm^3 is always larger than the mass measured by the LII.

42) Using an effective density (ρ_{eff}) of 0.55 g/cm^3 for the Small helicopter engine data improves the comparison between measured and modelled data for both number and mass. This result is consistent with the work of Hagen[a]. However, the analysis is not complete because the effect of shape may not have been applied correctly as the dynamic shape factor is unknown.

43) Using a size-dependent effective density could potentially improve the comparison between measured and modelled data for both number and mass.

44) Reducing ρ_{eff} increases the DGN for a given loss function. This may make results physically meaningful.

45) It is unlikely that particles are spherical, even at small sizes.

46) There is a need to check the correct particle diameter base is being used in the UTRC models because the particles are likely to be irregular shape in nature.

47) It is important to examine any fitted size distribution data as mathematical ‘tails’ at the small size will produce large artefacts when predicting exit plane distributions.

48) When predicted modal diameters are relatively large, where changes in penetration with size are small, the effects of changing the input values on DGN, facn (the fractional loss in number in the sampling system) and facm (the fractional loss in mass in the sampling system) are smaller than when the predicted modal diameters are relatively small, where there are significant changes in the penetration with size.

49) Further error propagation work needs to be performed to understand the amplified error impact on predicted engine exit concentration when either the mass and/or number instrument is below limit of quantification.

50) If either the mass or number instrument is below the limit of detection then the LLCA model will not provide an output and a different model methodology would need to be developed for predicting particle corrections for those engine data points. This would be an issue if the LLCA is used for certification methodology (for example, mixed vs unmixed engine exhaust sampling). The possible use of LLCA for airport emissions modelling needs to be assessed for these data points.

Specifically for the Small helicopter engine:

51) For both ρ_{eff} equal to 1 and 0.55 g/cm^3, the predicted number concentration at the exit plane are of the order 1e8 P/cm^3, which is in the concentration range where coagulation

[a] Hagen: “PM line loss correction without direct size measurement” 18th ETH conference on combustion generated nanoparticles, 2014.

could have an impact. If the loss functions are correct, the potential effects of this process need to be modelled to investigate the impact on DGN, facn and facm.

1. Structure of the Report

This report draws on a number of experimental tests, reviews and studies, each designed to broaden knowledge in a specific topic area concerned with developing a certification methodology for the measurement of aircraft non-volatile Particulate Matter (nvPM) emissions. It is intended that the information contained herein will be used to aid EASA and other regulatory bodies towards the development of future practices and certification procedures for non-volatile PM measurement in terms of mass and number.

Key Themes of the report are

- Maintaining the EASA/EU nvPM system (constructed within SAMPLEIII) to AIR6241 compliance
- Compare the EASAE/EU nvPM system with an engine manufacturer's nvPM system (namely Rolls-Royce) to provide further understanding of nvPM measurement uncertainty and comparison with existing SAMPLEIII data
- Assess the validity and operability of parameters specified in AIR6241 and ascertain whether it is possible to improve the methodology prior to it being turned into an ARP
- Perform nvPM measurement of different engine types, to assess the functionality of the measurement system specified in AIR 6241 with different probes, at different nvPM number and mass loadings at vastly different engine thrust conditions
- Assessing the validity of correcting the measured nvPM data to accurately predict engine exit nvPM emissions for local air quality modelling.

2. Introduction

The local and global effects of aircraft PM emissions are a key concern from the point of human health and climate change. Controls on aircraft emissions and maintaining compliance for local air quality standards on European airports is expected to be a significant issue in some cases. Whilst significant effort is being made to identify, quantify, model and predict these effects there is still a sizeable amount of development work required to produce a working specification for the absolute measurement of emissions of non-volatile particulate matter (nvPM). Both mass and number emission concentration will need to be measured in a format that can act as a standardised test under engine certification conditions. Other known aircraft emission challenges include accurate, traceable quantification of volatile emissions, especially aerosol precursors.

Control of nvPM emissions is one of the top priorities of the ICAO/CAEP (Committee on Aviation Environmental Protection). As an on-going step towards establishing a non-volatile PM Standard, CAEP, in February 2013, remitted its Working Group 3 (WG3) to:

> "Develop an aircraft engine based non-volatile PM mass and number metric and methodology for application as a non-volatile PM mass and number emissions certification requirement for turbofan/turbojet engines >26.7 kN. Note input from SAE International E-31 Committee." [Remit E14.01]
>
> "Develop an aircraft engine based non-volatile PM mass and number standard for turbofan/turbojet engines >26.7kN." [Remit E14.02]
>
> With a target date of February 2016.

WG3, with support of EASA and other Regulatory Agencies (Swiss FOCA, UK CAA, US FAA, Transport Canada & US EPA) requested the SAE E-31 to provide a non-volatile PM mass and number Aerospace Recommended Practice (ARP) document ready for formal approval by ballot of E31 members (a 'ballot-ready document') by February 2013. The SAE E-31 PM sub-committee had been working on developing appropriate sampling and measurement methods for aircraft non-volatile PM emissions, but expressed severe reservation about meeting the time scale requested by CAEP for a fully developed document.

EASA funded a 1 year study (known as the SAMPLE project), commencing in October 2008, which was one of the first collaborative programmes designed to evaluate the applicability of a number of modern measurement techniques whilst assessing the nature of PM. Conclusions from the original SAMPLE programme (EASA.2008.OP.13, 2009) suggested that calibration of the measurement techniques is critical. EASA then funded another year's study (SAMPLE II), which commenced December 2009. This collaborative effort was to determine the effect of the sampling line, in terms of its construction and operation on the exhaust sample being presented to the analysers compared with the exhaust sample at the engine exhaust plane. Conclusions from the SAMPLE II study (EASA.2009.OP.18, 2010) noted that sample line residence time appears to be a key parameter to PM losses and that VPR efficiency is difficult to analyse and hence a specific lower size PM cut-off may be required to reduce uncertainty. EASA then funded Specific Contract 01 (SC01) within SAMPLE III, a 4 year frame-work contract (EASA.2010.FC.10) commencing December 2010. This work developed a concept sampling system in terms of components, manufacture and operability.

Whilst previous studies during SAMPLE & SAMPLE II have quantified the nature of PM and the interaction between PM and the transport process used to convey it from the point of generation to the point of measurement, SAMPLE III (SC01) developed a robust well defined sampling system which significantly contributed to the SAE E31 concept for nvPM sampling.

Full scale engine test PM measurement system demonstration campaigns, within SAMPLE III (SC02), led to an improved confidence and understanding of specific elements of the sampling system. These were gained by operating and measuring behind aircraft turbine engines in parallel with a comparable SAE E31 concept PM sampling system (FOCA/EMPA) at SR Technics, Zurich. Following this engine test campaign and also another US/Swiss collaboration engine test, SAE E-31 could formally agree to a methodology on which to base an ARP. However, there were still some confidence gaps specifically on mass instrument calibration and performance, which were still to be addressed. As such, in order to achieve an established PM ARP methodology, several system inter-comparisons with engine manufacturer systems are required.

To accomplish this task, 'mobile reference' compliant systems (constructed and calibrated in compliance to AIR6241) were needed for engine manufacturers to compare to, at their own test facilities. Within SAMPLE III (SC03) a European EU/EASA 'mobile reference' system was developed for this task, and also obtained an initial system comparison datum, by undertaking comparative engine testing with both the North American (mobile) and Swiss (fixed) reference system, which provided a baseline for uncertainty expectations of future engine manufacturer system inter-comparisons. In order to ensure conformity of the EU/EASA system to AIR6241 a modification was made to the number measurement analyser under SAMPLE III (SC04).

AIR6241 "Procedure for the continuous sampling and measurement of non-volatile particle emissions from aircraft turbine engines" was published by SAE in November 2013. This document now serves as the basis for nvPM emissions measurements at the exhaust of aircraft engines.

SAMPLEIII SC05 provides the maintenance and calibration of the SAMPLE III EU/EASA mobile nvPM measurement system (compliant to AIR62141) so it can be used to carry out back-to-back measurements with other AIR6241 compliant sampling systems and to gather nvPM data at the exhaust of various aircraft engines.

An SAE nvPM ARP will be drafted on the basis of the experience gained from developing AIR6241, measurements within SC05, measurements at other engine manufacturers, the Swiss APRIDE study and the US VARIAnT study. This ARP is expected to be balloted in early 2015 and will support the ICAO/CAEP/WG3/PMTG request to develop aircraft engine non-volatile Particulate Matter (nvPM) emissions certification requirements.

3. Objectives of the study

The work detailed in this report is only determined with the implementing framework contract **EASA.2010.FC10 (SAMPLE III)** specific contract **SC05.**

The main purpose of this specific contract (**SC05)** is to apply the knowledge gained from the previous years of study (SAMPLE, SAMPLE II, SAMPLE III SC01, SC02 & SC03) along with that shared within the SAE E31 Committee, gained from full-scale aircraft engine testing using the maintained and calibrated European mobile reference and Rolls-Royce AIR6241 systems. In order to understand the variability, representativeness and check/improve the practicability and operability of the SAE E31 AIR 6241 compliant sampling system, and develop a ballot ready SAE ARP for the measurement of non- volatile PM mass and number.

EASA required the SAMPLE III consortium to conduct the following tasks in order to support the above objective:

Task 1: Contribute to the drafting of the ARP on the basis of AIR6241

Task 2: (a) Maintenance of the SAMPLE III AIR6241 compliant sampling system

(b) Measurements at the exhaust of aircraft engines

(c) Data analysis

4. Task 1: Contribution to the drafting of the ARP on the basis of AIR6241

4.1 Introduction

Significant progress was made within SAE E31 during SAMPLEIII SC03 reporting period to develop, produce and publish an "Aerospace Information Report" (AIR) detailing non-volatile PM measurement methodology in aircraft engine exhaust (AIR6241). In SAMPLEIII SC05 the consortium were tasked to assist in the development of AIR6241 towards an Aerospace Recommended Practice (ARP).

A number of focussed SAE E31 Technical Teams (Sampling, Mass measurement, Number measurement and Calculation methodology) - previously formed - were tasked to work together to define the methodology. These teams are overseen by a Co-ordination Group.

Dr. Mark Johnson had acted as the sampling team lead during the drafting of AIR 6241 and continued this role (as part of SAMPLEIII SC05) during the drafting of the ARP. He is a member of the SAE E31 PM ARP Co-ordination group and acted as the sponsor of AIR6241 which has aided in ensuring co-ordinated technical, regulatory and policy perspectives have been applied to the decisions taken in the development of the current draft ARP.

Following the publication of AIR6241, to move the methodology forward as an ARP, SAE E31 requires substantial robust testing of the methodology on engines (with relevant nvPM emission signatures) with appropriate sampling probe/rake geometry to ensure the original engine manufacturer's (OEM) confidence in the proposed sampling systems operability whilst creating datasets which may be used to establish measurement uncertainty and necessary for a successful ballot of the future nvPM ARP.

A detailed timeline highlighting the route forward for the development of a 'ballot-ready' ARP based upon expected OEM engine test dates was presented by Dr Mark Johnson during the SAE E31 annual meeting (Boston 2014) and is presented below in Figure 1. Note that the engine test campaigns discussed in detail in this report are shown on this chart.

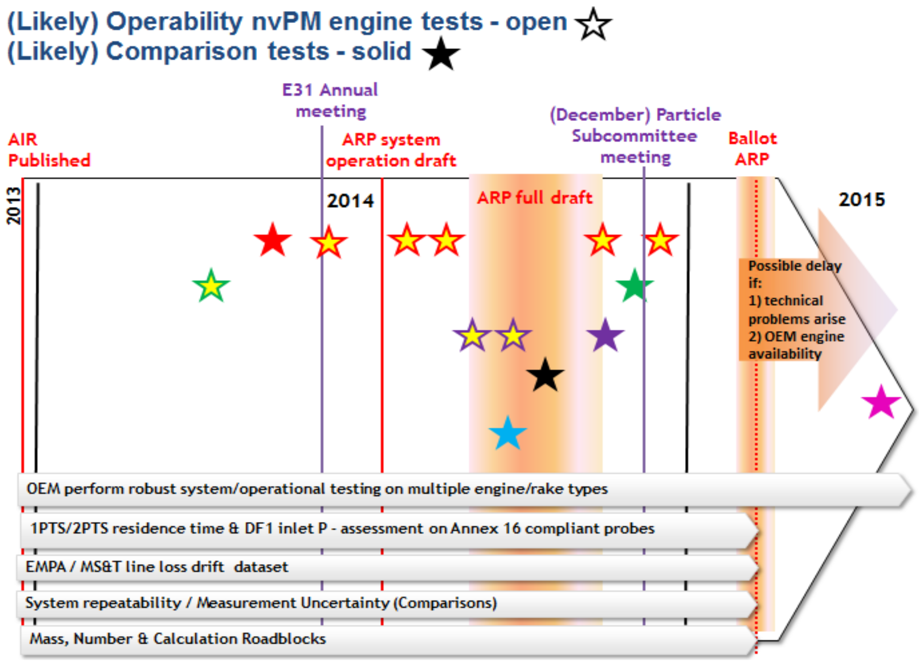


Figure 1 Proposed Timeline from AIR to ARP

It is seen in Figure 1 that with sufficient funding, utilising potentially planned engine tests, the balloted ARP is predicted to be ready early in 2015, with a caveat that this date is prone to slippage if there are unforeseen technical problems to overcome (or if OEM engine tests are cancelled or rescheduled). It should also be noted that effort will be required post-ARP ballot to address reducing the ARP compliant nvPM measurement uncertainty.

Based upon this proposed ARP timeline, a simplified timeline was established to provide SAE E31 information to PMTG in July 2014. Noting that this reported information also included reference to the line loss correction methodology also being developed within SAE E31.

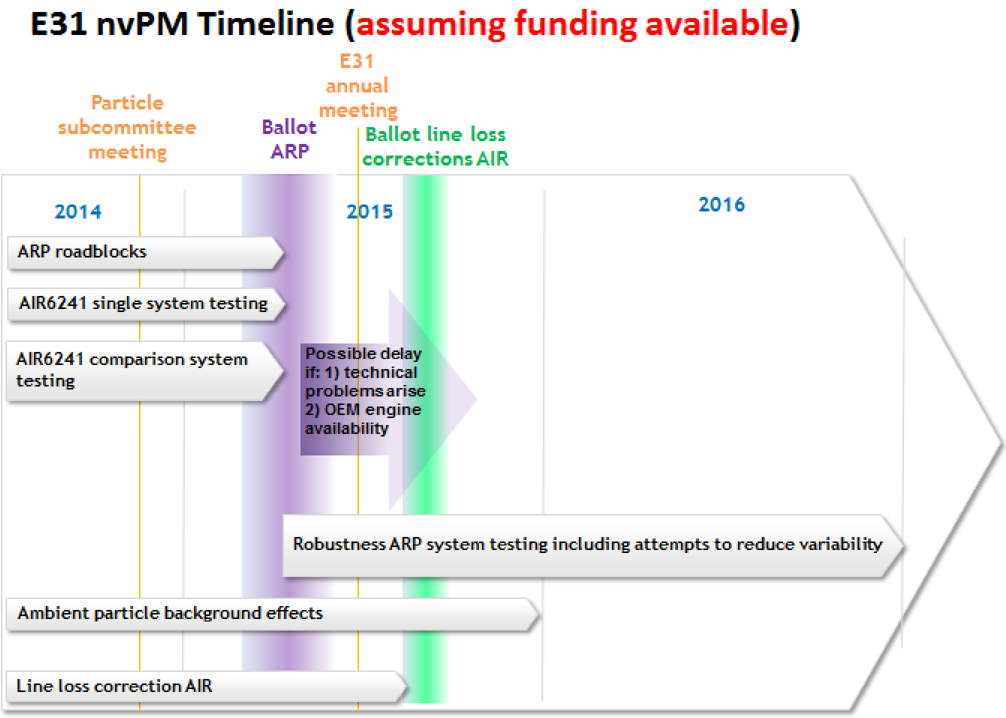


Figure 2 Simplified Proposed Timeline from AIR to ARP including reference to line loss AIR

4.2 Task 1a: Team lead of SAE E31 ARP nvPM sampling section

As discussed previously Dr Mark Johnson was team lead of the sampling section of AIR6241 and now holds this responsibility for the development of the ARP. He has been responsible for guiding the sampling team discussions in bi-weekly teleconferences along with leading dedicated sessions and discussion at annual SAE E31 Committee and PM sub-committee meetings.

Knowledge gained during these meetings has facilitated Dr Mark Johnson in drafting and editing the sampling section of AIR 6241 ready for publication by the SAE. He has kept the SAE E31 committee aware of uncertainties in the sampling system via a specific 'tracking spreadsheet' which highlights areas of research required to achieve a ballot-ready ARP. In addition he facilitated discussion on the types of possible back-to-back system inter-comparison testing which may possibly be performed at either OEM or research test sites and gained agreement that all the different types were useful to SAE E31. And initiated a quality spreadsheet detailing AIR6241 and draft ARP compliant engine test campaigns to enable SAE E31 to ascertain the quality of such tests.

Apart from utilising personal knowledge and building upon group SAE E31 discussions, many liaisons were required with individual SAE E31 members and external sources of information. All of which has helped to feed in information to continually build towards the ARP. This liaison discussion also included the initial building of a list of parameters to be passed on by OEM's to E31 as part of their ongoing nvPM engine test plans for PMTG.

In order to ensure that the appropriate SAE E31 issues were being addressed, Dr Mark Johnson was test co-ordinator of the SAMPLE III SC05, inter-comparison test campaigns (both full system and analyser only). This role not only involved campaign planning and co-ordinating the actual test,

ARP document timeline:

At the SAE E31 PM subcommittee meeting (3rd to 5th Dec 2013), the subcommittee reviewed data to ascertain system variability witnessed in SAMPLE III SC03/APRIDE5. After discussion regarding the observed variations in measurements agreement of the SAE E31 was gained enabling the ARP draft to be started; since this agreement the following schedule has been observed

- April/May, first ARP draft circulated prior to E31 annual meeting.
- 30th June, system operability section added (including spreadsheet checklist)
- 31st July, second ARP draft
- 19th September, third ARP draft
- Mid Nov, expected fourth draft prior to E31 PM subcommittee meeting in Dec 2014
- Possible ballot-ready ARP in Feb 2015

4.3 Task 1b: Team lead and contribution to the SAE E31 ARP operability section

During SAE E31 discussions on what was required to proceed from an AIR to ARP, it was clear that an ARP should be as clear as possible to the user of the document and that meant that a new User Operability section would be required. Dr Mark Johnson led the creation of the section and spent dedicated time in multi-day discussions with Prem Lobo (MS&T) to outline and build the new section. He also built separate check-lists for ARP users in time for the US VARIAnT study to be used in Sept 2014 which utilised AIR6241 compliant systems.

4.4 Task 1c: Contribution to nvPM line loss correction SAE document

An additional SAE E31 Technical Team was established to define a possible methodology for sampling system line loss correction. The timeline for this methodology is Q3 2015 and though this document is not required for a balloted nvPM ARP, the methodology is expected to be utilised by PMTG in the future to corroborate future airport local air quality models.

Both Dr Paul Williams and Dr Mark Johnson contributed to the discussions on this team about the proposed methodology. Specifically Dr Paul Williams trialled the methodology on the existing SAMPLEIII SC03 small helicopter engine dataset and fed back results and issues/conclusions via the team telecon's and the SAE E31 annual meeting in Boston. The methodology has been drafted into an SAE AIR document (Procedure for the Calculation of

Sampling System Penetration Functions and System Loss Correction Factors), though further understanding of the uncertainty of the methodology is still much needed and is discussed later in Section 7.5.

4.5 Conclusions of Task 1

1) Drafting of the SAE E31 nvPM ARP has started with significant progress made via a number of drafts throughout 2014

2) The SAE E31 nvPM ARP is currently on schedule for early 2015. The ARP's delivery date will depend upon proof of robust measurement and operational testing of the proposed nvPM system by all engine manufacturers.

3) Further nvPM engine and laboratory testing will be required post-ARP ballot if a reduction in nvPM measurement uncertainty is needed by PMTG.

4) An additional user operability section has been added to the draft ARP and provided in time to be used for other inter-comparison test campaigns such as the US VaRIANT study.

5) The particle line loss correction methodology has been trialled using an existing SAMPLEIII SC03 dataset with issues identified and communicated back to SAE E31.

5. Task 2a: Maintenance of the SAMPLE III AIR6241 compliant sampling system

5.1 Introduction

During the SAMPLE III SC03 project a mobile reference system was built by the consortium in full compliance with AIR6241, as described in EASA.2010/FC10 SC03[a]. The compliance in accordance with AIR6241 is shown in the SAE compliance tool spreadsheet (Appendix 9.1).

To help the reader a schematic breakdown of a AIR6241 compliant nvPM measurement system is described below in the following sections.

5.2 EU/EASA nvPM system overview

As discussed the EU/EASA nvPM system was built in compliance with AIR 6241 which lays out the sampling system equipment systematically in Figure 3 & Figure 4 respectively.
Note: PTS = Particle Transfer System and GTS = Gas Transfer System.

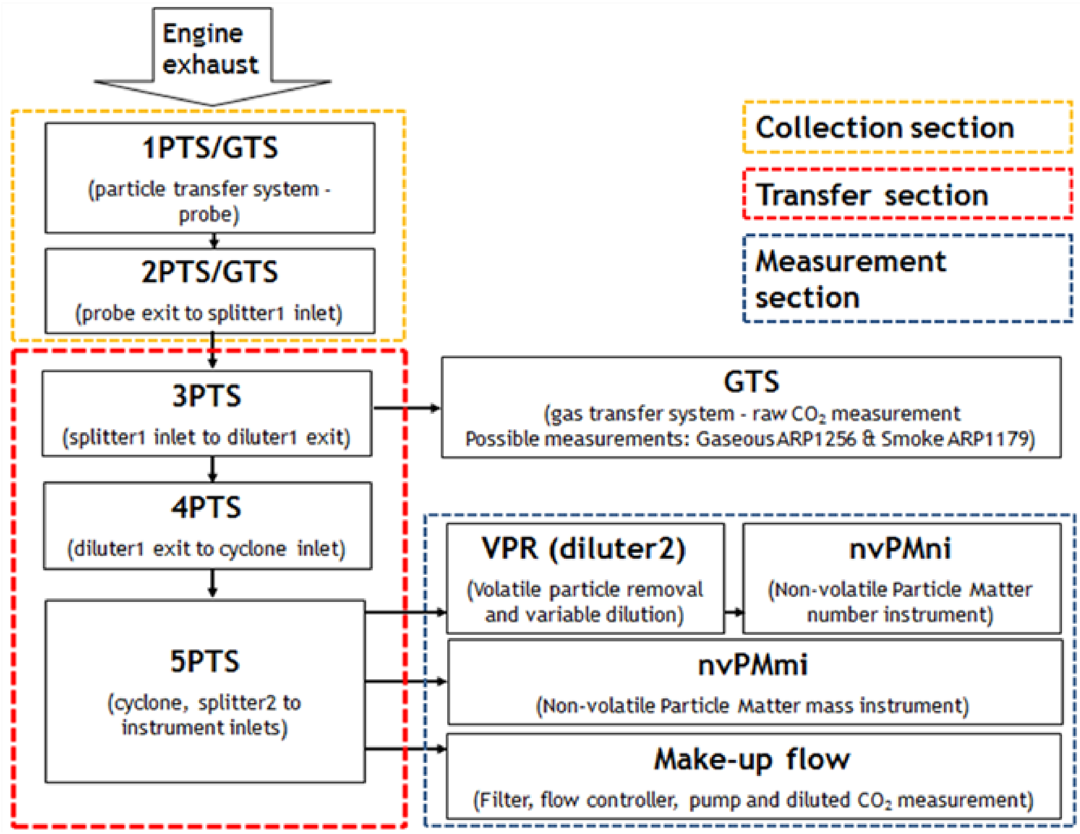


Figure 3 AIR 6241 Non volatile PM measurement system flowchart

[a] Please find at http://www.easa.europa.eu/project-areas/environmental-protection website

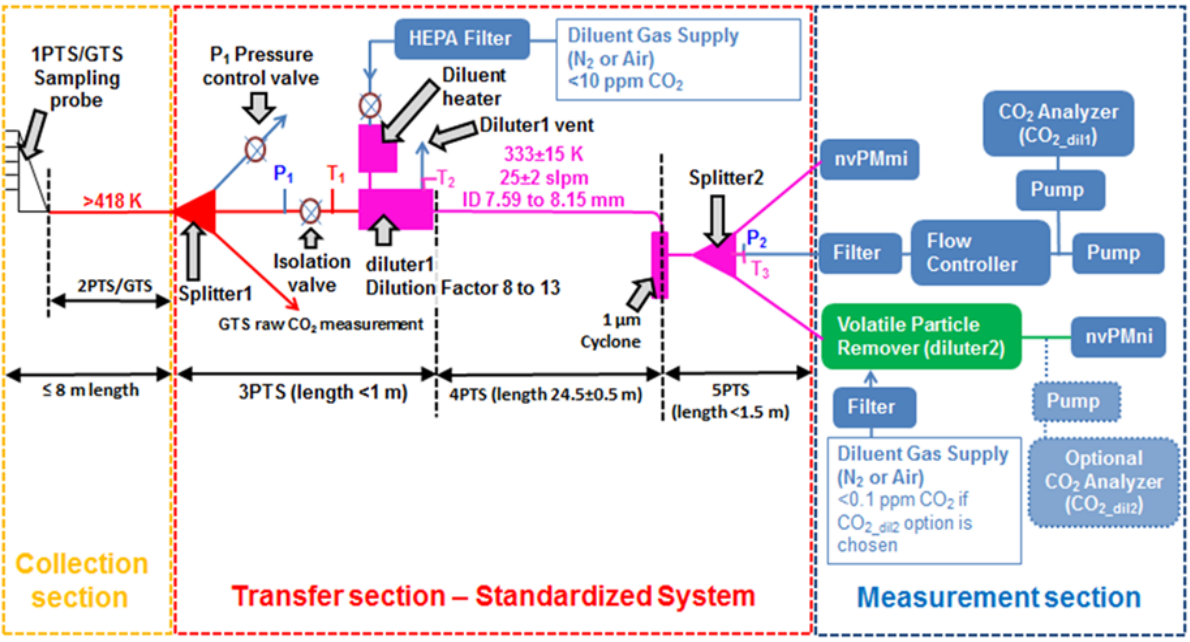


Figure 4 AIR 6241 Schematic of non volatile PM system

An AIR6241 compliant system can be split into three distinct sections namely the collection, transfer and measurement sections, with a more complete summary of conformance provided later in Section 5.5. Differences in system construction and operation between the EU/EASA reference system utilised in SC05 and SC03 measurement campaigns, are provided with reasoning in the following sections.

5.3 Mobile EU/EASA nvPM system components

As discussed the EU/EASA nvPM system was constructed to be in compliance with both AIR 6241 and with suggestions laid out by the SAE E31 PM subcommittee for reference systems. The EU/EASA nvPM system's instrument components are as follows-

Mass Instruments-

As per the recommendation of the SAE E31 PM subcommittee both a Laser Induced Incandescence (Artium LII300) analyser -which measures the radiance of superheated soot particles to a known mass relationship - and an AVL Micro Soot Sensor (MSS 483), - which measures the mass through the heat induced vibrations in the aerosol- are employed each measuring off the same splitter in the heated distribution oven (5PTS)

Number Instrument-

A fully compliant AVL Advanced Particle Counter (APC 382), is utilised as the number concentration measurement system and works on the principle of passing aerosol through a diluter then catalytic stripper before being further diluted and measured by a condensation particle counter – where each particle is grown through a butanol medium to a sufficient size to be optically counted.

Size Measurement-

In addition to the recommended AIR 6241 nvPM mass and number measurements, where possible additional size measurements were also taken using a Differential Particle Sizer

(Cambustion DMS-500) and Scanning Mobility Particle Sizer (TSI SMPS nanoDMA), these measurements allow appraisal of actual line losses to be conducted.

A more thorough description of the measurement analysers is given in SAMPLE III SC02[a], as such they will not be further discussed at this time.

5.3.1 Additional Splitter and heated lines (2PTSa)

To operate the EU/EASA nvPM system in a full system inter-comparative test with the Rolls-Royce nvPM system it was necessary to add an additional splitter and sample line (2PTSa) - upstream of Splitter 1 - into the suggested AIR 6241 compliant nvPM sampling system in agreement with recommended practices of the SAE E31, details of this addition are shown in Figure 5 below. The sample lines used to act as 2PTSa are nominally identical to those used in SAMPLE III SC03, being constructed from trace heated conductive PTFE hose of internal diameter 8 mm and a length 2 m.

In order to facilitate the full sampling system inter-comparison and obtain Annex 16 compliant gas analysis (CO, NOx, UHC) and Smoke Number, it was necessary to utilise a 3 way 10 mm OD (8 mm ID) splitter with 30° angle, which was purpose built to the AIR 6241 specifications by the SAMPLE III consortium and trace heated to 160 °C.

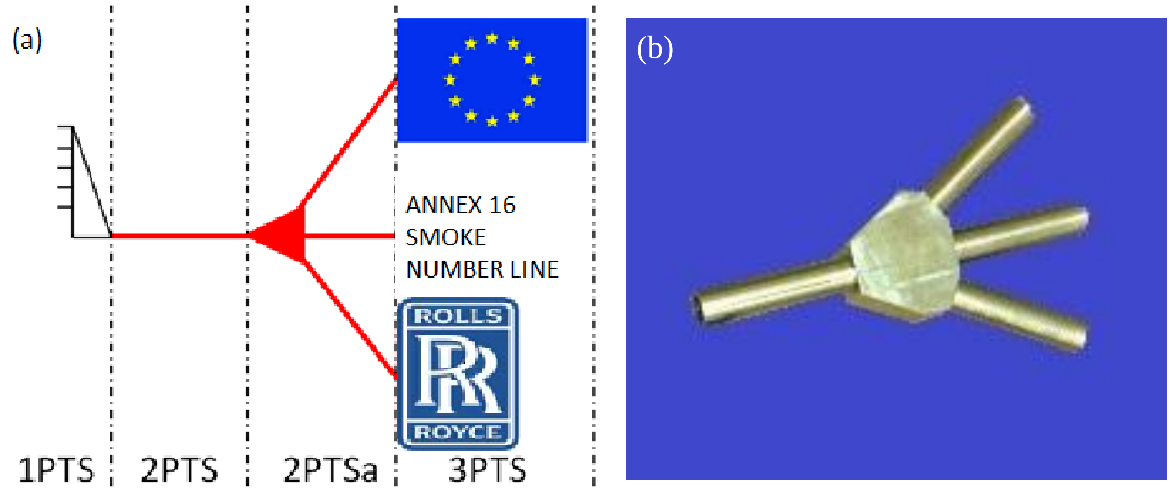


Figure 5 (a&b) Schematic representation and photograph of additional sampling section splitter (2PTSa) respectively

5.3.2 Measurement Section

The fully assembled rack mounted EU/EASA nvPM system with the instrumentation, data acquisition and control is shown below in Figure 6.

[a] Please find at http://www.easa.europa.eu/project-areas/environmental-protection website

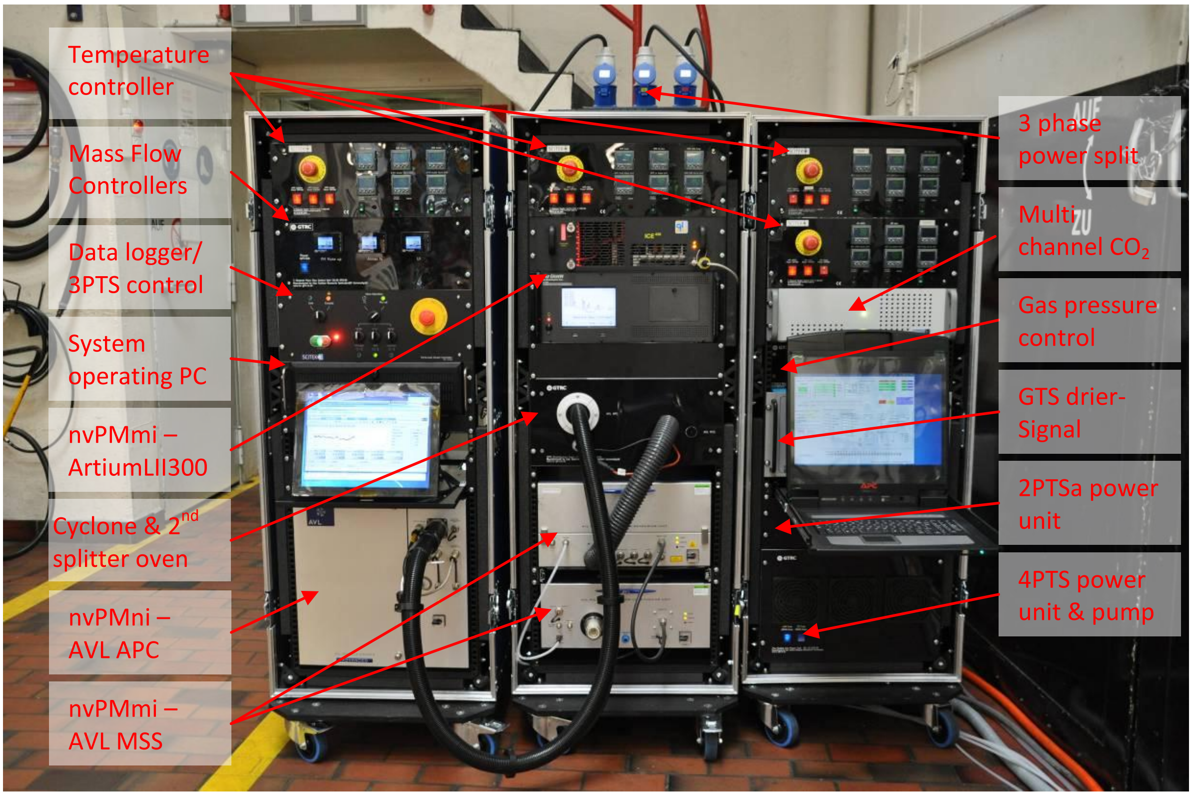


Figure 6 Control, data acquisition and measurement sections of mobile EU/EASA nvPM system

5.4 EU/EASA nvPM system Calibrations

To ensure that the EU/EASA nvPM system was compliant with AIR 6241 specifications it was necessary to have all relevant analysers and systems calibrated prior to shipping the unit for testing.

Maintenance of the compliant sampling system has involved calibration and service of the individual components of the system, calibration certificates for the analysers in accordance with AIR 6241 protocols are presented in Appendix 9.5, with a summary of individual calibrations given below.

5.4.1 Non Volatile Number Measurement System Calibration

In November 2013, the APC unit was re-calibrated addressing issues with the previous AVL calibration. There was an adjustment in the Catalytic Stripper set point temperature to the AIR6241 compliant temperature of 350 °C and there had been misrepresentation of both ambient temperature and 15 nm count efficiency as noted on the calibration certificate presented and discussed in EASA.2010/FC10 SC03, as the CPC was still within its prescribed annual calibration done in June 2013 so this was not recalibrated. In June 2014, a calibration that was performed by TSI Inc., UK. This calibration was conducted in order that the system was in compliance for the test campaign at Rolls-Royce Derby on the large in-production engine, described in Section 6.3.2.

In order to satisfy the contractual conditions of SAMPLE III SC05 and to re-synchronise calibration schedules between the APC and the CPC, the AVL APC with associated TSI CPC was returned to AVL Graz in October 2014 for a full annual AIR6241 approved nvPM number measurement instrument calibration. Within this calibration, VPR performance in terms of penetration and volatile particle removal was confirmed. along with the number counter linearity and counting efficiency slope and cut point.

As noted in EASA.2010/FC10 SC03, the AVL certificate documentation was lacking detail and discussions took place between the SAMPLE III consortium and AVL representatives that have led to a new certificate being issued. The EU/EASA reference system current calibration certificate – presented in the new format confirming adherence to AIR6241– is presented in Appendix 9.5.1.

5.4.1.1 *TSI CPC Calibration*

As discussed earlier to ensure compliance for the Rolls Royce, Derby large engine test the EU/EASA reference system CPC (model number 3790E, S/N 3790132002) underwent a full AIR6241 compliant calibration and service in June 2014. The linearity and counting efficiency for this and the previous year's calibration are shown in Figure 7 and summarised in Table 1 respectively. Comparison of the 2013 linearity calibration shows a negative drift of circa 2 %. In the latest 2014 calibration the linearity was shown to be within 6 % which was again within the AIR6241 specification of ±10 %.

The counting efficiency of the EU/EASA reference system CPC also showed a decrease from the 2013 results: for 10 nm particles the counting efficiency had dropped from 53.2 to 51 % over 12 months but then increased to 56.8 % for the latest calibration, and at 15 nm the counting efficiency had dropped from 98.1 % to 93.7 % and then further to 91.4 %. All these calibrated values are within the AIR6241 allowable specifications of 50 %; and 90 % respectively but show fluctuations either due to the instrument counting efficiency drifting and/or the measurement uncertainty in the counting efficiency methodology.

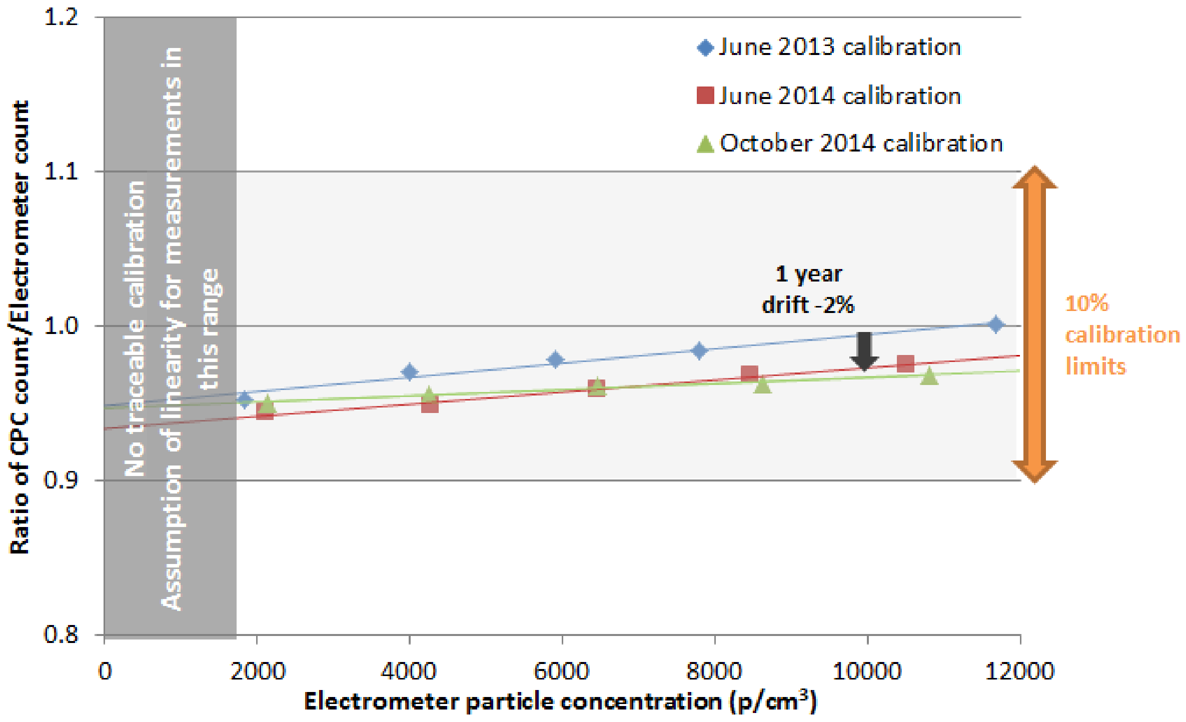


Figure 7 Comparison of CPC calibration data over 1 year

In summary, the EU/EASA reference system CPC is still within AIR 6241 specifications (even accounting for drift in both the linearity and the counting efficiency). These drifts in values may be as a result of CPC maintenance during the annual service (performed by TSI prior to calibration). As such it is not possible to ascertain whether these changes in counting efficiency and linearity are as a result of CPC drift or are a result of any maintenance adjustment to the analyser prior to calibration.

To try and assess this in the future it was decided at the SAE E31 annual meeting that CPC manufacturer's should be approached to see if they would be able to provide an 'as found' calibration before any settings were adjusted prior to the annual calibration, however at present this is not a service offered yet by TSI.

Table 1 Comparison of the CPC counting efficiencies across a period of 18 months

	Particle Counting Efficiency (%)			
Size Cut-point	June 2013	June 2014	October 2014	AIR 6241 spec.
10 nm	53.2	51.0	56.8	≥50
15 nm	98.1	93.7	91.4	≥90

5.4.1.2 *AVL APC penetration*

As explained above, the June 2013 AVL AIR6241 calibration was performed with a low Catalytic Stripper (CS) temperature. A comparison of the performance with respect to CS temperature with the more recent calibrations is shown in Table 2 below.

Table 2 Numerical penetration performances of the EU/EASA nvPM system VPR at different Catalytic Stripper temperatures from June to November 2013 at 100 PCRF setting

	Particle Mobility Size (nm)			
Catalytic Stripper Temperature (K)	100	50	30	15
573 (June 2013)	77%	72%	62%	32%
623 (Nov. 2013)	72%	68%	60%	39%
623 (Oct. 2014)	72%	67%	58%	36%
AIR6241 spec.	≥70%	≥65%	≥55%	≥30%

It can be seen that the penetration efficiency for smaller particles slightly increased for the higher CS temperature of 623 K, compared to the measured value in the previous calibration which was performed at the lower 573 K set point, this result is in contradiction with decreases in penetrations noted for the other mobility sizes prescribed at 30, 50 and 100 nm. This increase in penetration would go against the expected result of extra losses associated with the increase in thermophoretic loss but may be explained by additional measurement uncertainty of the smallest 15 nm diameter particles. Note that there is no impact on SAMPLE III SC03 data, as there was an assessment of VPR penetration in comparison to a VPR operating at the AIR6241 compliant CS temperature as part of that engine test campaign.

The VPR penetration drift performance (with CS at correct temperature) over 12 months between June 2013 and October 2014 is shown below in Figure 8. It can be observed that all the calibrations are within AIR6241 specification (all data points unity/1.0). The penetration efficiency has slightly decreased over the 12 months period, and it appears the decrease increases at smaller particle sizes (especially at 15 nm). However, this may be due to additional measurement uncertainty of the smallest 15 nm diameter particles.

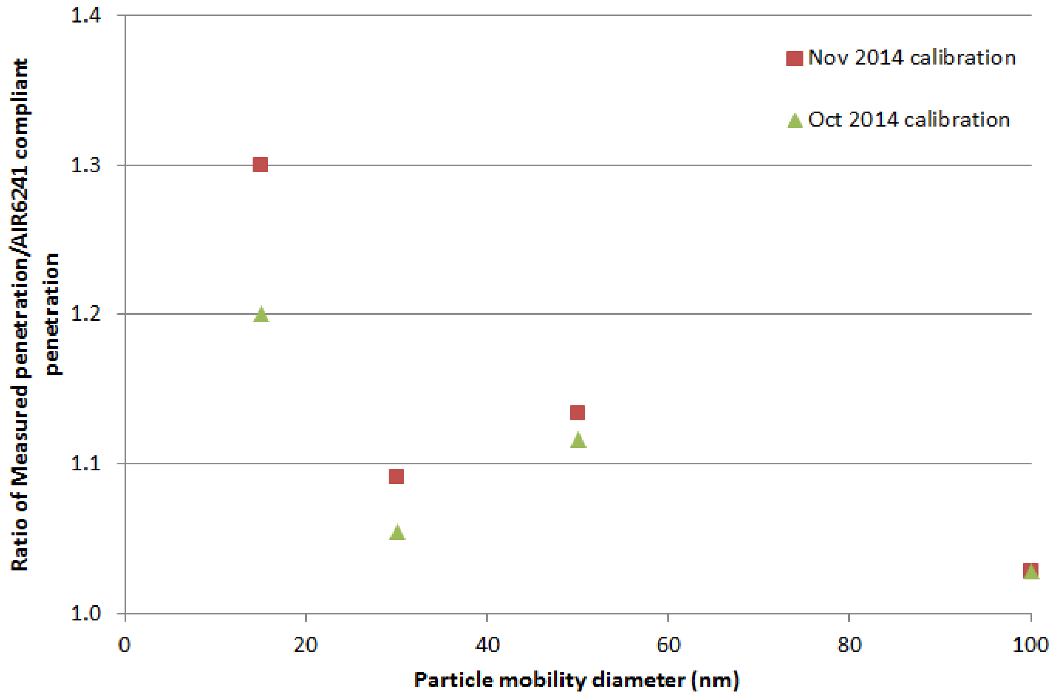


Figure 8 Penetration performances of the EU/EASA nvPM VPR at different particle sizes for different AIR6241 compliant calibrations over a period of 12 months

5.4.1.3 *AVL APC Dilution Factor Check*

The Particle Count Reduction Factor (PCRF) relates to an automotive industry number parameter specified by the PMP protocol for the measurement and subsequent regulation of nvPM in Diesel Engines. The factor is a multiplication correction factor combining both the dilution factor and an approximated VPR particle loss (effectively assumed as that of a 50nm diameter particle). Therefore a PCRF set-point equates to a dilution factor set-point in the AVL unit.

As detailed in AIR6241 the dilution factor must be verified for the AVL APC at the different dilution set-points used during testing. It is a requirement that the value be measured using gaseous measurement prior to testing. As such using pure CO_2, the EU nvPM system was checked at PCRF values of 100 through to 3000 with the values measured listed in Table 3 below.

During engine test particle measurements the AVL instrument measures the 'online' PCRF based upon APC diluter parameters. Typically the online PCRF varies within 2 % of the set-point. All data in this report has been corrected based upon the pre-test dilution factor check for each specific PCRF set-point and thus does not include correction for particle losses within the APC instrument. It should however be noted that at PCRF settings of 2000 and 3000 (shown by the orange shading in Table 3), the CO_2 concentration measurements measured by the NDIR CO_2 analyser were below 20 % of the analyser full scale range, which is outside the recommendation of ARP1256: "Ideally, the sample gas concentrations shall be in the 20 to 95 % of scale range".

The variation of dilution factor from calibrated to observed can be seen in Table 3 for all the PCRF values measured as can be seen for a PCRF of 100 the measured dilution factor was approximately 61, 8.2 % lower than compared to the value of 66 quoted by AVL in the instrument annual calibration, at a PCRF of 250, again the EU/EASA nvPM system was within tolerance measuring a dilution factor of 167 compared to the calibrated value of 169. At the highest PCRF of 3000, gaseous measurements determined a dilution factor of 2105 compared to the calibration value of 2038. All of these variances are within the tolerable AIR6241 specification of 10 % agreement and can be attributed to uncertainties in measurement during calibration and gaseous measurement. However it is noted that there is good consistency with previous values of dilution factor calculated via CO_2 measurement during the SAMPLE III SC03 test campaign, with near identical results for both PCRF 100 and 250.

Table 3 Calibrated and measured dilution factors for EU/EASA reference AVL APC's at ambient sample pressure inlet conditions and comparison with SC03 measurements

PCRF setting	Prior Calibration DF2 (AVL)	Post Calibration DF2 (AVL)	Measured DF2	% difference (to prior cal.) (10% limit)	SC03 Measured DF (at low/typical sample pressure)
100	66	65	61	8.2	61 (63)
250	169	171	167	1.4	166 (167)
500	340	340	340	0.0	-
1000	687	674	699	-1.8	-
1500	1011	1011	1042	-3.0	-
2000	1325	Not performed	1351	-2.0	-
3000		2038	2105	-3.3	-

In SAMPLE III SC03 the consortium observed that the calibration was performed at ambient pressure – not the pressure at which the device is typically operated during testing – hence additional dilution factor checks (in addition to those prescribed in AIR 6241) were conducted at reduced pressures. While the SAMPLE III SC03 results showed an increased dilution factor, the mean variation was small and within 2 %, such that in SAMPLE III SC05 the dilution factor check was performed at ambient pressure increasing operational simplicity.

As discussed previously it is noted that the EU/EASA nvPM system is within the 10% AIR6241 specification for dilution factor discrepancy, but this study reaffirms the importance of pre-test dilution factor checks if real time online measurement of dilution factor is not being undertaken, to insure any drift in dilution factor since calibration is accounted for.

5.4.2 Mass flow controller (MFC) calibrations

Careful control of all the flow conditions for the PM and gaseous sampling, lines is stipulated by AIR6241. Where needed (LII, make-up and raw lines), the sample mass flows in the EU/EASA system are controlled by Bronkhorst EL-Flow F-201CV-10K-ABD-22-V. These MFC's offer mass flow control in the flow range of 0-15 sLPM at an accuracy of ±0.5 % RD (residual deviation) plus ±0.1 % FS (full scale).

The MFC calibration certificates from 2013 are shown in the SAMPLE III SC03 report. The certificates from 2014 are in section 9.5.3. A comparison between the calibrations is shown below in Table 4.

Table 4 Comparison of MFC measurement uncertainty and drift over 16 months

MFC serial number	2013 calibration Residual (%)		2014 calibration Residual (%)	
	Mid-flow	Full flow	Mid-flow	Full flow
M13204236A	0.01	-0.06	-0.13	-0.20
M13204236B	-0.06	0.00	-0.10	-0.19
M13204236C	-0.09	-0.13	-0.06	-0.13

It is observed that there has been minimal drift over the time period between calibrations and that all the residual measurements are well within the stated instrument accuracy of 0.5 % residual deviation plus 0.1 % FS.

5.5 EU/EASA system maintenance/modifications

5.5.1 General

To make the EU/EASA reference nvPM system more compact, an upgrade of the network equipment was made, adding the capability to remotely operate the system and individual analysers wirelessly with either laptops or tablets, which also acted as additional visual display units allowing simultaneous control of multiple analysers by numerous operators. This modification allowed for removal of the built-in touchscreen unit – facilitating a smaller system footprint which was deemed necessary given the limited space at some of the proposed test locations.

During the re-commissioning and procedural optimisation testing at the Rolls Royce helicopter engine test facility, there were communication issues with the Signal 3 channel CO_2 NDIR gas analyser, as it was not possible to quickly resolve this issue the decision was made to acquire redundancy in an additional 2 channel CO_2 analyser.

For the tests conducted at Rolls-Royce Bristol, an extended 25m long umbilical line was built to provide supply power and temperature control and acquisition for the 2PTSa splitter and 2m sample lines. This addition facilitated the EU/EASA nvPM system and the Rolls-Royce system to be controlled and compared remotely – with a more thorough description given in section 5.3.1.

Between the lean burn staged engine and large in-production rich burn engine tests, the EU/EASA system sampling lines were modified to eliminate the requirement of low voltage transformers - used in previous SAMPLEIII SC03 tests - in favour of inducted heating coils, this modification was as a result of an operational audit that indicated this new approach would offer a safer, more robust (reducing risk of failure) and smaller system.

5.5.2 Dilutor cleanliness and geometry

Though all three reference sampling systems compared in SAMPLE III SC03 were operated in compliance to AIR6241, there were differences observed in the primary sampling system dilution factor (DF1), even though they were constructed from similar Dekati DI-1000 diluters sampling at similar inlet pressures and driven at comparable dilution pressures. It was observed that both the EU/EASA and North American systems operated at a higher DF1 than the Swiss system. The geometries of the 3PTS inlet between all systems were very similar thus it was surmised that the differences in DF1 could be due to three things:

1) Differences in Primary Diluter vent geometry resulting in additional backpressure on the diluter exhaust – on comparing the three systems it was noted that the Swiss vent has the largest bore (18 mm) and shortest length (few cm), the EU/EASA system has a smaller bore (12 mm) and longest length (30 cm), and the North American system has the smallest bore (7.7 mm) bore and medium length (20 cm).

2) Primary Diluter cleanliness. Without frequent checking it is unknown if there is any build-up of soot inside the diluter's inlet nozzle which would change the diluters effective nozzle orifice diameter hence leading to a change in flow dynamics, and resultant dilution factor.

3) Additional GTS flow rate in the Swiss system (due to extra gas analysers) resulting in a localised lower pressure at the 2PTSa splitter leg inlets, when compared to the EU/EASA and North American systems (and therefore at the inlet of the subsequent diluters) resulting in a difference in dilution factor.

To address items 1 & 2, the EU/EASA reference system primary diluter was cleaned and the diluter vent diameter increased to 18 mm (the maximum achievable with the bore of the 25.4 mm (1") ball valve added to the diluter vent to facilitate a back-purge capability recommended by the SAE E31 in case of diluter nozzle blockage during a test campaign).

The Dekati DI-1000 used in the EU/EASA system had not been internally cleaned since new and has been involved in a number of gas turbine test campaigns over the past 5 years as listed below and partially described in previous SAMPLE reports:

Small helicopter engine testing
SAMPLE I HES combustor rig
SAMPLEII HES combustor rig
AAFEXII (loaned to MS&T) On-wing large engine testing
SAMPLEIII.SC01 APU testing
SAMPLEIII.SC02 Multiple large engines at Zurich
SAMPLEIII.SC03 Multiple large engines at Zurich
SAMPLEIII.SC03 Small helicopter engine testing

To clean the diluter, the manufacturer's recommendation was followed, utilising an ultrasonic bath. The diluter was disassembled and photographs of the DI-1000 diluter components prior to the cleaning process are presented in Figure 9.

It can be clearly observed that there has been heavy particle deposition on the internal surfaces of the inlet of the diluter nozzle. This is not surprising as there is a thermal gradient across this wall (cooler diluent on one side at ~60 °C and hotter sample gas ~160 °C on the other) which will cause a thermophoretic loss. There is also significant build-up of soot inside the nozzle orifice.

Where the (HEPA filtered) diluent enters and impacts the surface of the nozzle there appears to be a small amount of soot deposition, it is noted that the remainder of the external nozzle surface is clean.

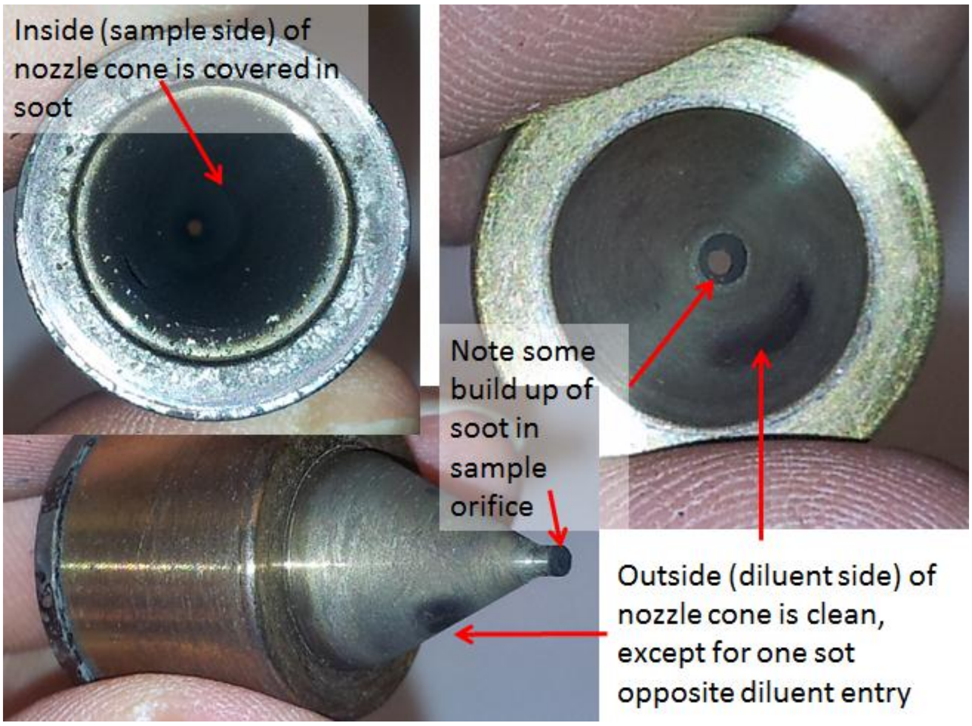


Figure 9 Photos of ejector dilutor nozzle prior to sonic bath cleaning

No deposition was observed at the diluent orifice outlet, thus the soot spot must be formed from recirculation of soot entering through the nozzle.

At initial inspection the diluter mixing chamber appeared clean, however, taking a swab of the surface highlighted a light ‘dusting’ of soot deposition on the internal surfaces.

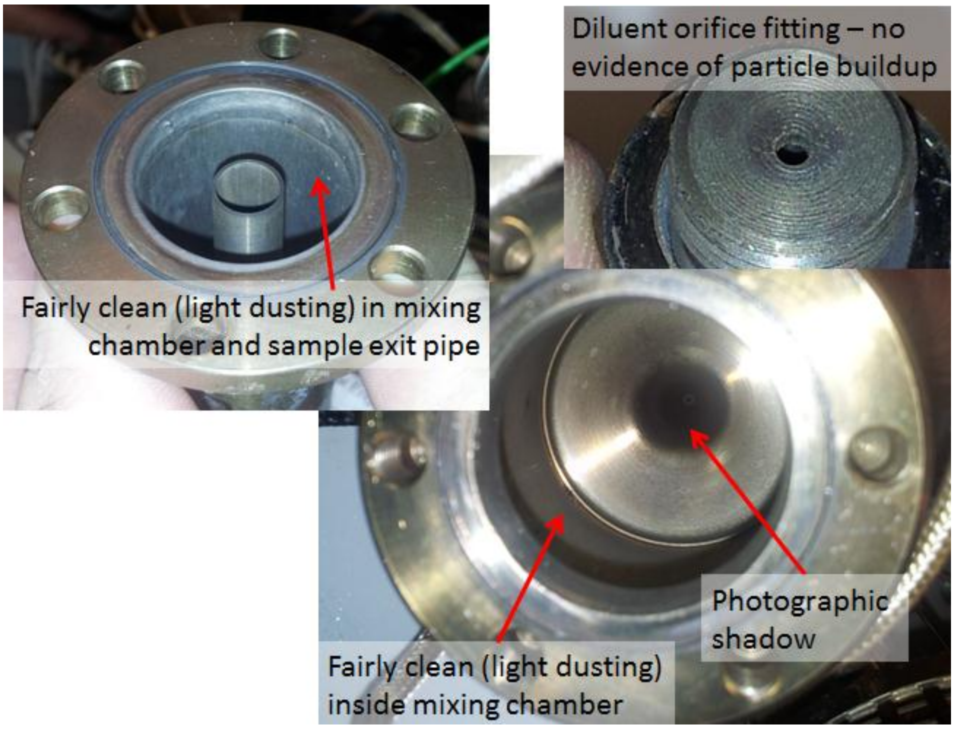


Figure 10 Photos of dilutor mixing chamber prior to sonic bath cleaning

Unfortunately the diluter was reassembled and reincorporated back into the EU/EASA reference systems primary splitter and dilution unit (3PTS) before additional photos could be obtained. However, the technician confirmed that after cleaning and prior to reassembly all surfaces resembled an electro-polished finish with no evidence of soot deposition remaining.

Subsequent data shown in Figure 25 (paragraph 7.2.4) shows that the primary dilution factor range (DF1) experienced during the SAMPLE III SC05 system comparison test after cleaning and exhaust geometry modification was lower than witnessed during SAMPLE III SC03 test at similar inlet pressures and diluent pressures. For clarity the data is simplified in Table 5 below.

Table 5 Primary dilution factor ranges for SAMPLEII SC03 and SC05 engine test campaigns

	DF1 Lower Range	DF1 Upper Range
SAMPLE III SC03	9	12
SAMPLE III SC05	8	10

It is difficult to assess whether the change in vent geometry or the cleaner nozzle (increased aperture size) led to the decrease in DF1 for the EU/EASA system. However, it should be noted that communication with the Swiss system operators indicated that their diluter nozzle was not partially blocked like the EU/EASA system. Though the narrowing of the orifice due to soot deposition likely contributed towards an increased DF1 in SAMPLEIII SC03, it is also likely that the expanded change in vent geometry also contributed to the observed decrease in primary dilution factor in SAMPLEIII SC05.

It is suggested that if the primary dilution factor is observed to increase over a period of multiple engine tests, that the operator should investigate the cleanliness of the primary diluter, and clean using new cleaning protocols being developed within the SAE E31 for inclusion in the nvPM ARP.

5.6 EU/EASA nvPM system training

For the first time in SAMPLE III, a suitably qualified dedicated research engineer (Dr Yura Sevcenco) was employed to act as test operator for all the test campaigns. To ensure competency and familiarisation with the EU/EASA reference system, a training programme was undertaken including testing the system on a small helicopter engine. This was done with all the previous operators of the system present for this new engineer and a research fellow from the University of Manchester (Dr Paul Williams). From this exercise new SOP's for the EU/EASA reference system were developed by the new operators as discussed later. The EU/EASA reference system generally required two operators to be present during testing. However the scheduling flexibility engendered by having a dedicated staff member whom was always available allowed a greater range of support for the system for maintenance and actual engine testing.

5.6.1 Documentation

During the system training programme, the new operators went through several days of training and induction including gaining a thorough knowledge of each individual analyser used in the EU/EASA reference system utilising and amending the draft Standard Operating Procedures (SOP's) for the MSS and APC suggested by the SAE E31. As discussed previously modifications and review of the EU/EASA nvPM system SOP along with a test day check-sheet was developed which is presented in Appendix 9.8, with a description following in section 5.7.

5.7 EU/EASA system operational checklist

A system SOP and checklist were developed for the EU/EASA system, to ensure consistency in measurements and conformity to AIR 6241. The procedures (developed initially for the lean burn staged engine test at Rolls-Royce Bristol) will be applicable for future synchronised parallel sampling campaigns. However these SOP's had to be further amended for the large in-production engine test held at Rolls-Royce Derby, as due to current operational site limitations the EU/EASA nvPM system was operated in conjunction with the Rolls-Royce nvPM system including primary dilution and splitter box (3PTS) and sampling line (4PTS). The check-sheet for the in-production engine test was thus simplified; removing the dilution box control, allowing the operators to focus only on instrument operation.

A copy of the newly developed checklist can be found in Appendix 9.8.2.

5.8 EU/EASA nvPM system Conformance

A completed (format modified version) of the most recent (version 6) SAE E31 AIR 6241 PMTG compliance tool is presented for the entire system, of the EU nvPM system in Appendices 9.1 to 9.4; the spreadsheet includes system setup, mass and number calibration, system and instrument calibration.

5.9 Conclusions of Task 2a

1) The EU/EASA nvPM system was fully calibrated and maintained for the system inter-comparison testing during SAMPLEIII SC05 to AIR6241 compliance

2) Calibration of equipment is time intensive (taking up to 6 weeks in the case of the AVL APC) and scheduling this in accordance with engine testing was difficult.

3) Dedicated training for operational staff and clear system operating procedures are required to ensure smooth operation of an nvPM measurement system. Specific small engine test training and the writing of standard operating procedures and checklists for the EU/EASA nvPM system has been performed.

4) Maintenance of the equipment has been simplified by having a dedicated operational staff; along with the benefit of improved design changes, brought upon by specific testing issues.

5) The primary Dilution Factor should be monitored over time (multiple test campaigns), as part of routine maintenance, to determine when the diluter nozzle orifice needs cleaning, however it is perceived that the newly installed back purge facility will reduce this requirement.

6) Long term drift should be monitored of all nvPM instrumentation to establish the confidence level. Further effort is needed to work with instrument manufacturer's to change internal practices and provide "as found" calibration prior to instrument service maintenance procedures, as a routine to provide better understanding of instrument drift.

7) The dilution check for the VPR (DF2) is an important part of the nvPM system operability. Up to 10 % variability is allowed with values of 8 % being observed, for the lowest PCRF setting of 100. Reducing this variability could reduce overall nvPM EI uncertainty.

6. Task 2b: nvPM Measurements of aircraft engine exhaust

6.1 Introduction

The SAMPLE III consortium conducted inter comparisons of two AIR 6241 compliant reference systems, namely: the EU/EASA mobile reference system - developed for EASA during the SAMPLE III SC03 research contract- and the Rolls-Royce mobile system.

An experimental programme was developed. This body of work included performing:
- Back-to-back full system comparison (on a modern lean burn staged engine)
- Back-to-back analyser comparison (on an in-production rich burn engine)

In addition:
- Single system (RR) measurements on two further in-production engine models (Turbofans >26.7 kN thrust) were also performed.

The single RR system measurements are not given in this report due to engine data confidentiality. The data will be presented to EASA in the form of an emission regulation report and subsequently provided to CAEP PMTG feeding much needed data into the group responsible for the setting of the new nvPM regulatory standard. It should be noted that both these tests were witnessed by EASA and were obtained using the same RR nvPM system compared against the EU/EASA system.

For the system and analyser comparisons, the data analysis (Chapter 7) compares the SAMPLE III SC05 inter-comparison data with previous SAMPLE III SC02 and SC03 data.

6.2 Rolls-Royce nvPM system description

Due to design confidentiality issues, it is not possible to provide a detailed description of the RR nvPM system in this report. However, it is possible to state that the RR nvPM system has been shown to comply with AIR6241 with relevant information being shared and accepted by the European aviation regulatory authority (EASA).

For the SC05 inter-comparison analysis it is important to note that the same types of mass analyser were compared on both the systems, namely the LII300. Further data analysis is provided comparing the two alternative types of mass instrument installed in the EU/EASA system.

6.3 Experiment Overview

The data published here was obtained from two different engines operated at RR Bristol and RR Derby test cells in the UK, with relevant descriptions of both experimental setups presented in the following sections.

6.3.1 Lean burn Staged engine test description

6.3.1.1 *Engine Description*

The Lean burn staged engine was an emission demonstrator vehicle for current lean burn technology. It was representative of a Turbofan engine with >26.7 kN thrust. The lean burn combustion system operates in different stage modes: up to part power the Pilot flame only is fuelled, at higher powers additional fuel is added providing an overall lean flame with a rich core.

6.3.1.2 *Test schedule*

Multiple engine test points were obtained between low and high power at a range of combustor inlet and injector/staged conditions.

Eight inter-comparison test points (T1 to T8) were possible prior to an emissions equipment hardware failure relating to maintaining the sample at the required temperature to both nvPM systems. More additional data points were obtained with the RR nvPM system in singular operation in between the inter-comparison points.

Testpoints T1 to T4 were obtained under pilot only conditions. Whilst T5 to T8 testpoints were obtained under staged combustion conditions.

6.3.1.3 *EU/EASA and RR System Installation at RR Bristol*

For the first nvPM measurement system inter-comparison the full EU/EASA reference system was compared against the comparable Rolls Royce system, with the installation being integrated into an existing infrastructure. The probe and the particle transport line to the 3PTS dilution boxes are covered later in more detail in section 6.3.1.4.

The 2PTSa splitter was located around 1 to 1.5m from the dilution boxes (EU/EASA and RR), which were located securely on a gantry alongside the engine. The Annex 16 and 4PTS sampling lines (both 25 m in length) and the 2PTSa umbilical's were fastened to the gantry staircase railings and run to an access port in the outer test cell wall which allowed them to be connected to the respective measurement systems, housed outside the test cell.

A schematic outlining the Particle Transfer System is shown below in Figure 11.

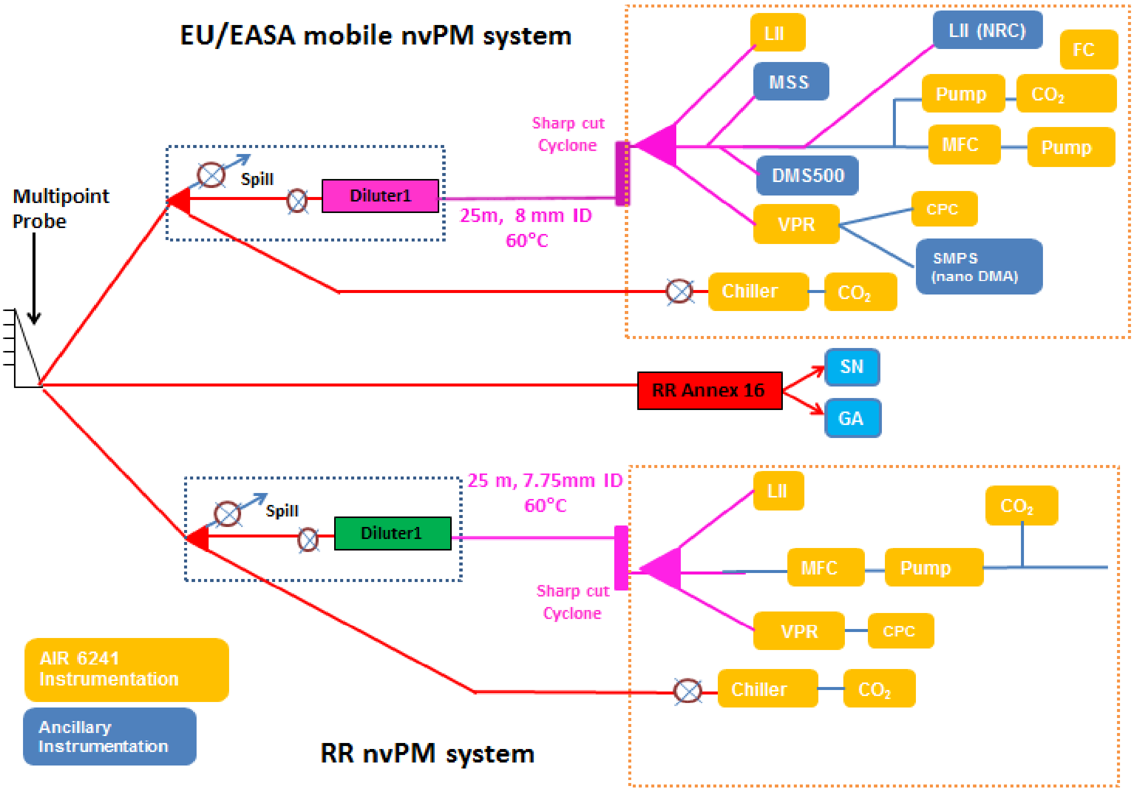


Figure 11 Schematic of EU/EASA and RR system inter-comparison

The EU/EASA nvPM system was installed in a test caravan (supplied by Rolls Royce) located outside the testbed in which the lean burn staged engine was tested, a photograph of the test caravan is shown in the top left of Figure 12. To facilitate the EU/EASA nvPM system into the test caravan, RR removed caravan hardware and infrastructure to provide enough internal physical space. Additionally an extra 3-phase electrical power supply and a compressed air supply to provide the needs of the EU/EASA nvPM system was installed.

The Rolls-Royce Emissions measurement van was parked behind the test caravan; with the RR nvPM system hardwired into the RR emissions van (which is fully mobile) hence allowing comparisons to be made of the identical RR system at both the Bristol and Derby test facilities.

Located suitably near to both measurement systems was the diluent and calibration gases (also shown) required for the compliant operation of the nvPM systems.

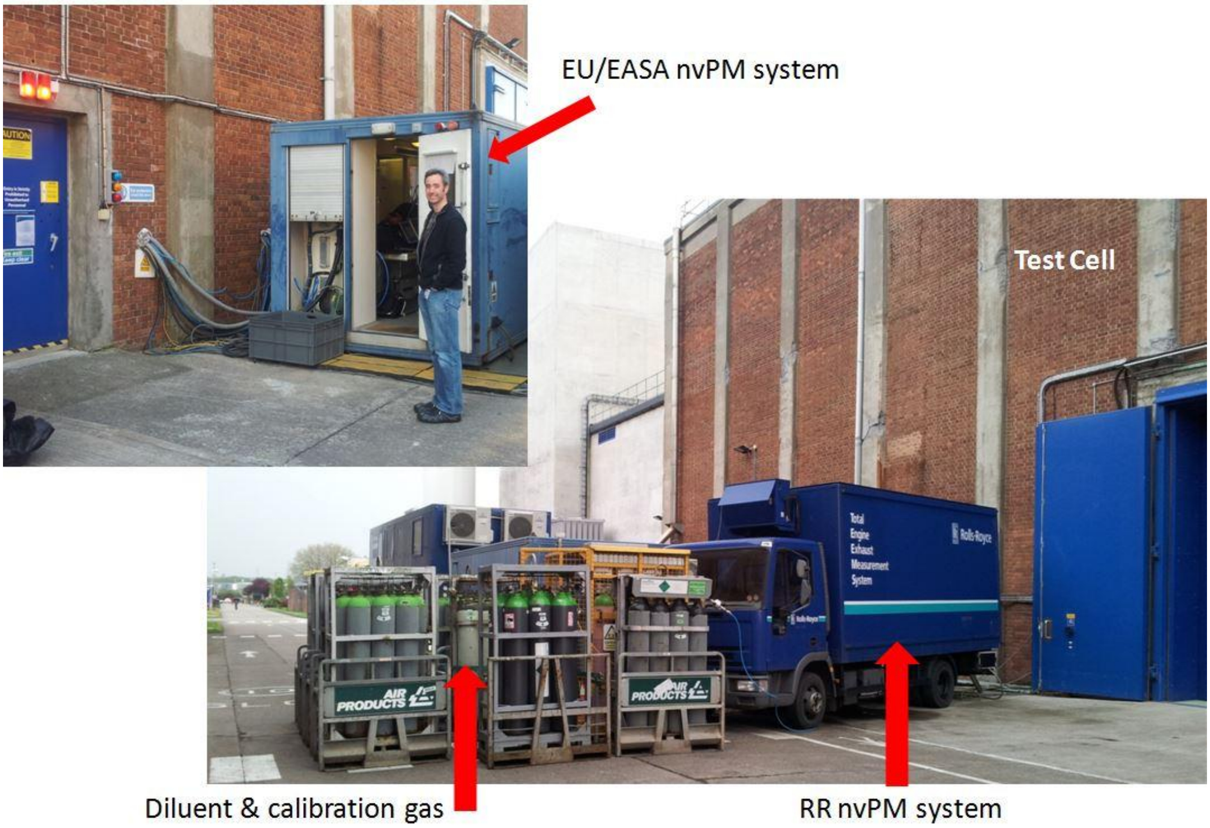
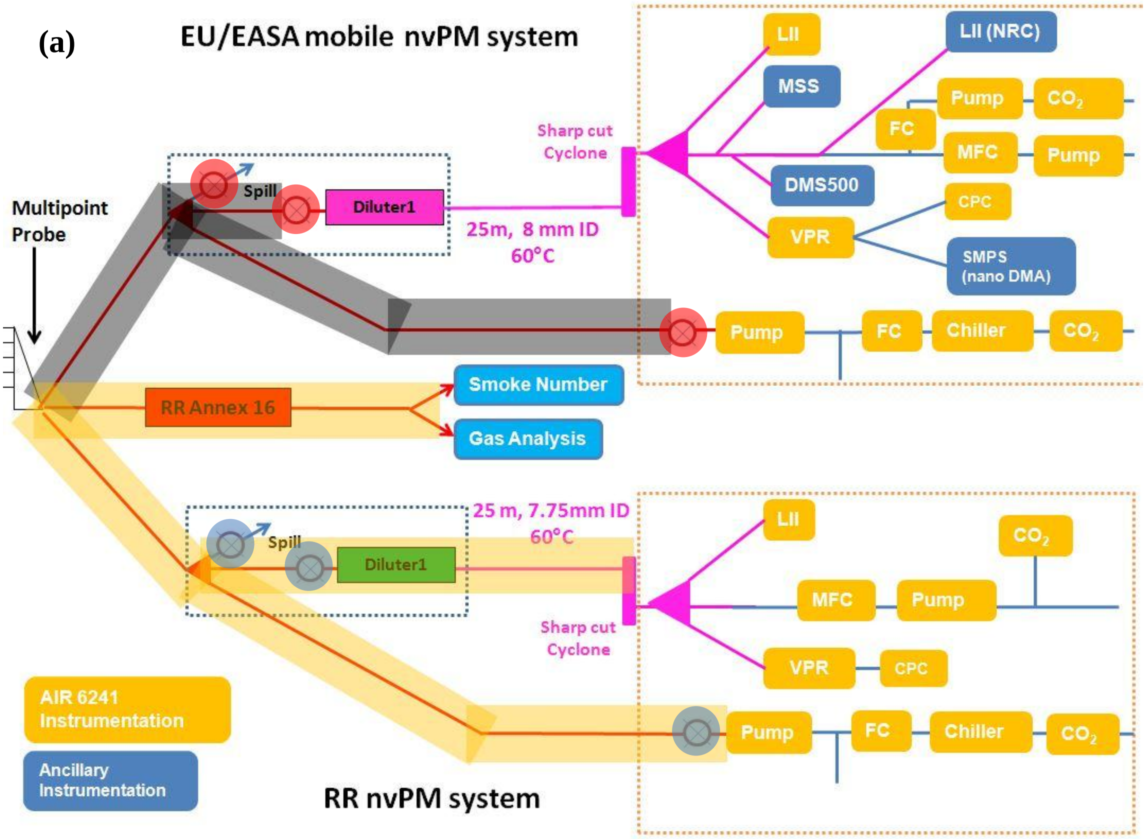


Figure 12 Photographs of Lean Burn staged engine test campaign

The original design intent was for the Rolls-Royce and EU/EASA nvPM systems to be operated simultaneously in parallel. However, sample pressure fluctuations were observed on the initial simultaneous parallel tests and the decision was made to run the systems sequentially for each test point so as not to risk damage or data integrity.

The sequential test programme involved gas analysis and Smoke Number measurement on the Annex 16 line (after initial test point was recorded, a constant gas flow was always maintained). Firstly the Rolls-Royce nvPM measurement was then used followed immediately by the EU/EASA nvPM system both recording the results for the same engine test condition. The flow diagrams at the time of measurement of each system can be seen below in Figure 13 (a & b) respectively: the Rolls-Royce measurement, shown in the top schematic; and the EU measurement, underneath, where the orange shade shows the exhaust flow and the grey shaded areas depicting isolated sampling systems.

(a)


EU/EASA mobile nvPM system
Multipoint Probe
Spill
Diluter1
Sharp cut Cyclone
25m, 8 mm ID
60°C
LII
LII (NRC)
MSS
Pump
CO2
FC
MFC
Pump
DMS500
CPC
VPR
SMPS (nano DMA)
Pump
FC
Chiller
CO2
RR Annex 16
Smoke Number
Gas Analysis
25 m, 7.75mm ID
60°C
Spill
Diluter1
Sharp cut Cyclone
LII
CO2
MFC
Pump
VPR
CPC
Pump
FC
Chiller
CO2
AIR 6241 Instrumentation
Ancillary Instrumentation
RR nvPM system

(b)

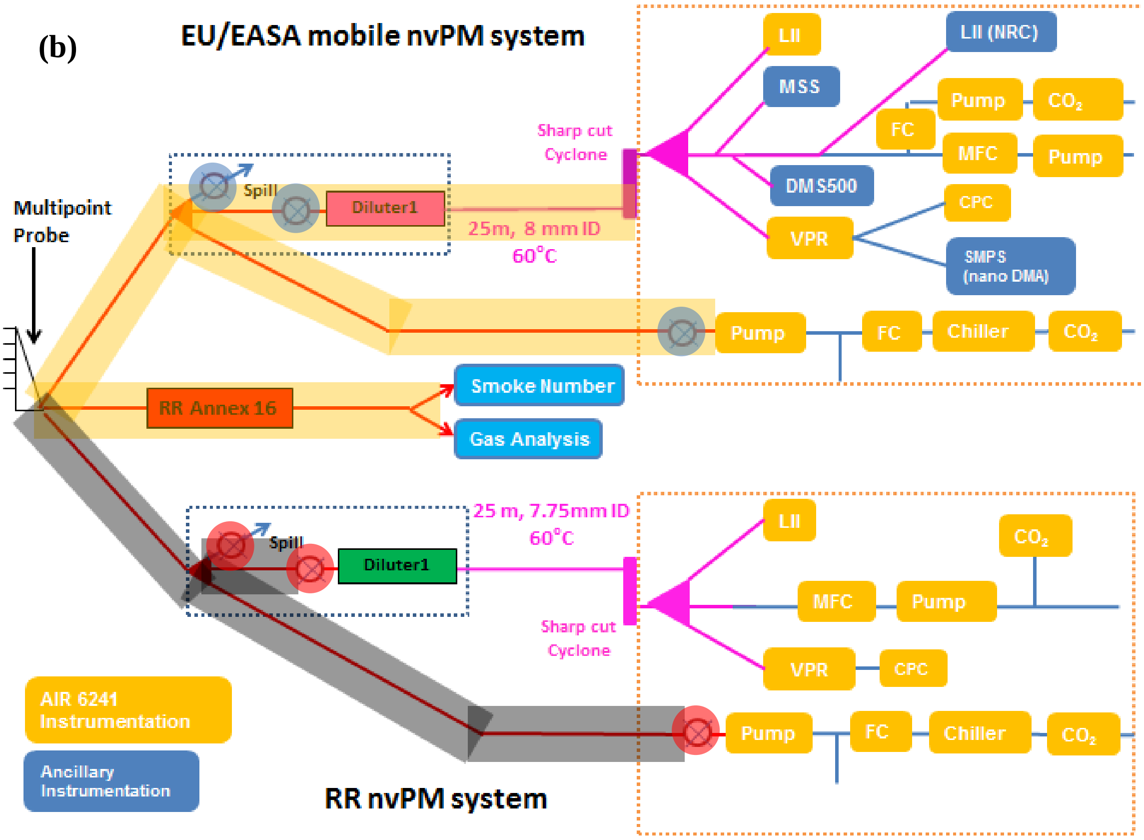

EU/EASA mobile nvPM system
Multipoint Probe
Spill
Diluter1
Sharp cut Cyclone
25m, 8 mm ID
60°C
LII
LII (NRC)
MSS
Pump
CO2
FC
MFC
Pump
DMS500
CPC
VPR
SMPS (nano DMA)
Pump
FC
Chiller
CO2
RR Annex 16
Smoke Number
Gas Analysis
25 m, 7.75mm ID
60°C
Spill
Diluter1
Sharp cut Cyclone
LII
CO2
MFC
Pump
VPR
CPC
Pump
FC
Chiller
CO2
AIR 6241 Instrumentation
Ancillary Instrumentation
RR nvPM system

Figure 13 (a-b) System operation schematic – grey shade indicates no flow, orange shade indicates flowing sample. Blue circles indicate OPEN valves, Red circles indicate CLOSED valves.(a) Top schematic is RR measurement ; (b) Bottom schematic is EU/EASA measurement

6.3.1.4 *Additional System Setup detail*

This section details the additional parts of the sampling system outside of the RR and EU/EASA nvPM compliant systems and are facility/engine dependent.

Sampling Probe (1PTS)

A fixed multi-arm and multi-point probe with rakes designed to collect a representative averaged sample both radially and circumferentially. The design of the probe was built to Annex 16 specifications but not traversable. The carbon balance matched within 5 % and therefore the probe is deemed to be combustion representative.

Primary Sample line (2PTS & 2PTSa)

This section of the sampling system was common to both the EU/EASA and RR sampling systems. This section was 8 m in length, and constructed geometrically to maintain the 80 % pressure drop at the probe inlets and additionally provide extra spill capability due to the large number of probe orifii for this particular sampling rake. The line was insulated and temperature controlled to ensure the sample did not drop below 160 ºC.

6.3.1.5 *System Operability*

The EU/EASA and RR systems were operated in accordance with AIR6241 throughout all the engine testing. A completed (format modified version of the most recent (version 6) SAE E31 AIR 6241 PMTG compliance tool is presented for the EU/EASA system, for the operation of the EU/EASA reference system in Appendices 9 (note also includes calibration).

In addition the test was witnessed by an independent EASA representative to ensure both RR and EU/EASA systems were operated in compliance to AIR6241.

6.3.2 In-production rich burn engine test description

6.3.2.1 *Engine description*

The in-production engine tested in Derby was a large modern rich burn turbofan engine with a thrust >26.7 kN.

6.3.2.2 *Test Schedule*

The planned engine test schedule consisted of two power curves with 20 test points to provide a detailed curve from which the ICAO LTO points (7, 30, 80 & 100%) could be obtained.

Prior to the initial power curve the AFR (prove carbon balance) 4 point curve was planned with additional time built into the schedule specifically for gathering the extra 4PTS line length inter-comparison data at two of the test points.

Unfortunately only two power condition measurements were obtained at different low engine power conditions prior to a severe test bed malfunction which forced the emissions test to be rescheduled to a later date beyond the schedule of the SAMPLE III SC05 test programme.

However, at the two measurement points (P1 and P2), valuable data was obtained allowing both an analysis of the extra 4PTS line length connected to the EU/EASA and RR 5PTS ovens and also additional nvPM measurement analyser comparisons between the EU/EASA and RR systems. The latter analysis facilitated an improved analysis of the full system-to-system inter-comparison performed on the lean burn staged engine earlier in SAMPLEIII SC05.

6.3.2.3 *EU/EASA and RR systems installation at RR Derby*

The installation of the EU/EASA nvPM system at Rolls-Royce Derby had several difficulties, in part due to restrictions in available mounting points on the probe support structure and possible increased 'test bed flow blockage' for the 3PTS dilution box, and restricted route through test bed walls for the multiple heated and umbilical lines (Cost to make physical changes to a single test bed to enable dual fitment of systems were estimated to cost ~70 kEuros), this meant only one nvPM system dilution box could be fitted at a time. However, this facilitated a useful experiment for E31 which could provide a dataset that would separately determine the measurement uncertainty of the nvPM instrumentation only. Thus providing an understanding of the split of overall measurement variability between instrumentation and sampling system. The possibility of performing full sampling system intercomparison is therefore facility dependent which will have an impact on the possibility of performing such tests in the future.

The installation of the two nvPM systems was located within a building thus a specific test caravan was not needed for the EU/EASA system (though careful sample exhausting was required). RR installed an additional 3-phase electrical power supply and provided a compressed air supply for the needs of the EU/EASA nvPM system.

Both the EU/EASA system and RR measurement sections were coupled to the RR Annex 16 compliant rake (1PTS and 2PTS), 3PTS dilution box and 4PTS line see Figure 17 a to d). To facilitate this setup, a new splitter system (built to be compliant with geometrical specifications of AIR6241) was incorporated at the end of 4PTS (prior to cyclone inlet) with additional temperature controlled trace heated stainless steel lines being used to connect to the EU/EASA and RR cyclone and distribution ovens (5PTS). The available physical space for system installation, ease of operation (including safe switching access) and geometry conformance to AIR6241 provided the limitations for the potential extra 4PTS line length. The shortest possible length was determined to be 0.9 m. The dual measurement system comparison installation is shown below in Figure 14 with details of the sample switching system described further below (Figure 15).

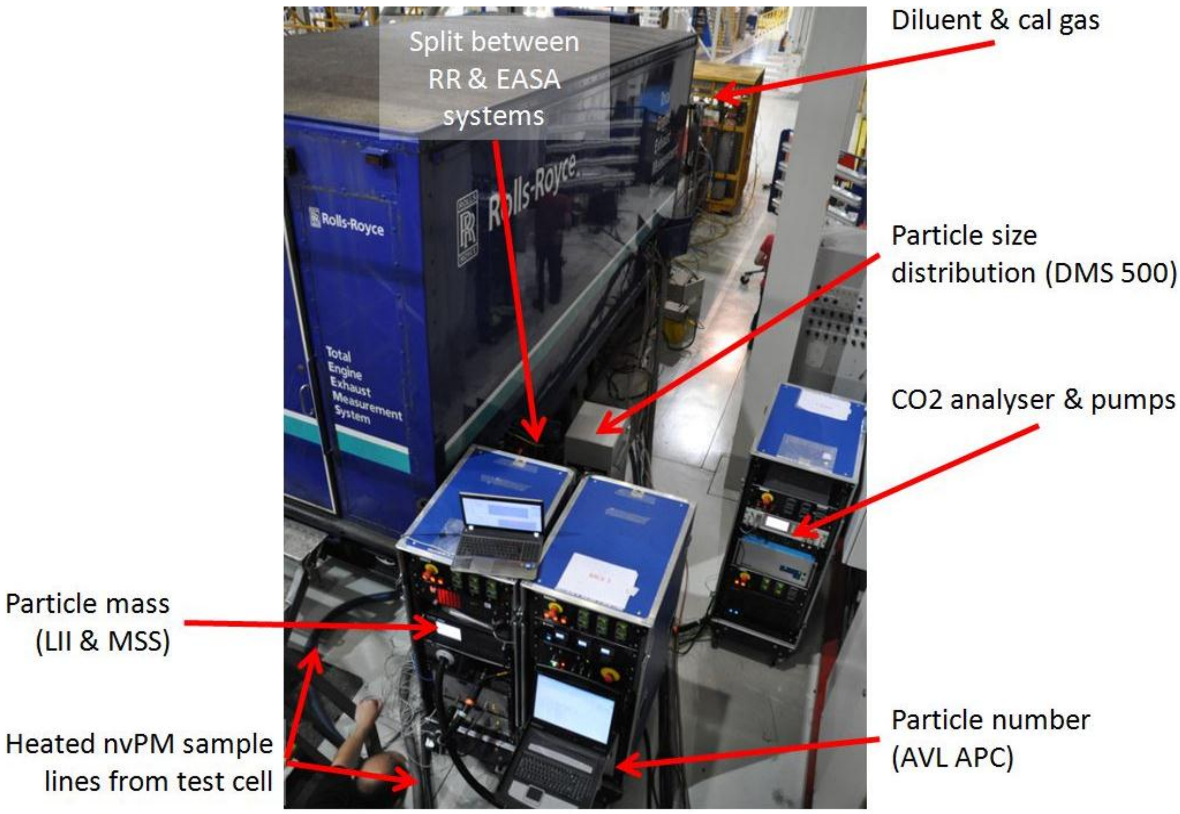


Figure 14 Photograph of In-Production Rich Burn engine setup

With the responsibility for the control of 2PTS and 3PTS systems conducted by Rolls-Royce, the operating procedures required for the operation of the EU/EASA nvPM system were significantly reduced as discussed previously, to instrument management and assisting with the valve control for switching between the two nvPM systems, which is described in more detail in the following section.

6.3.2.4 *System setup*

Sampling Probe (1PTS)

The sampling probe used was Annex 16 compliant and consisted of 4 rotating arms with multiple probe orifii measuring from the core flow only of the engine being tested. The probe/rake setup and stand was equivalent to that used in SAMPLE II with further detailed drawings of the setup presented in that report[a].

4PTS switching system

As can be seen below in Figure 15 and Figure 16, both 4PTS and GTS required bespoke switching systems in order to splice the EU/EASA nvPM system onto the RR system. The switching system and associated pipe work is AIR6241 compliant with multiple thermocouples (three K-Type per seamless tube length) to maintain the diluted sample at 60 °C. The splitter used conformed to the 30° requirement and full-bore ball isolating valves were used to isolate one branch or the other for measurements by the RR or EU/EASA nvPM systems.

[a] Please find at http://www.easa.europa.eu/project-areas/environmental-protection website

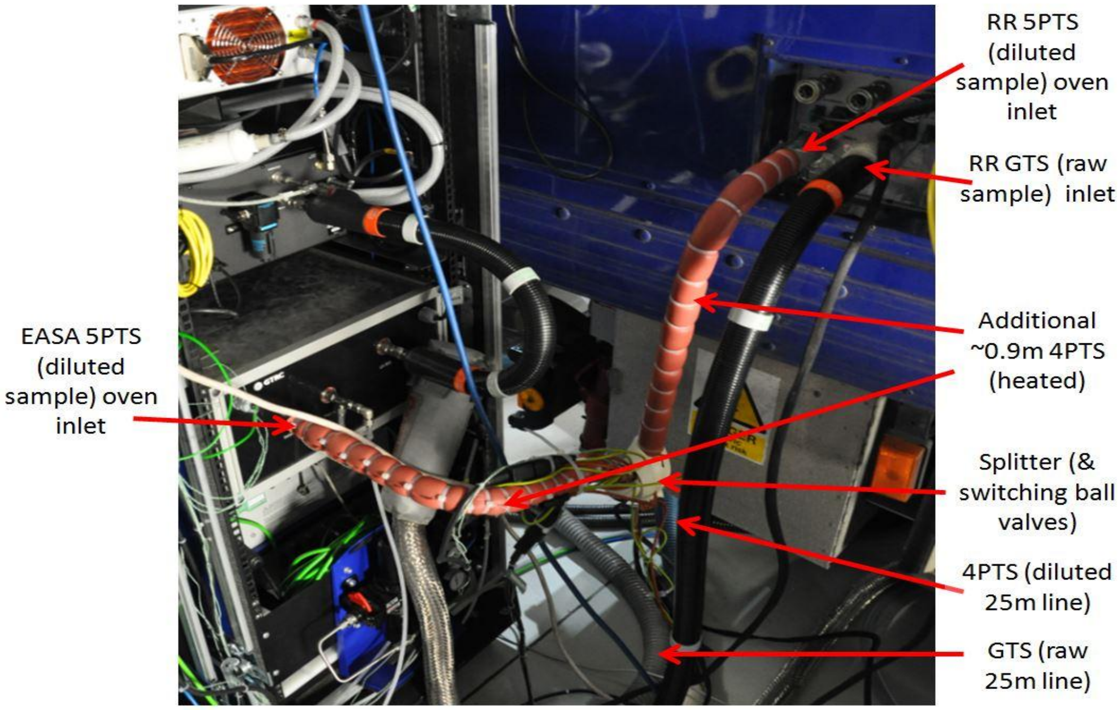


Figure 15 Photograph of 4PTS switching system installed

Tests were conducted to show that there was negligible variation in results with the 0.9m addition in the 4PTS splitter set-up (Figure 17 c and d), these are discussed later in the analysis section.

The GTS line also had a splitter and valves installed, shown below in Figure 16, necessary for the raw CO_2 values needed to confirm the primary dilution factor for the nvPM results.

A sequence of events on test points was agreed with the Rolls-Royce emissions crew to reduce delay and minimise disruption. The system operation order schematics are shown in Figure 17 (a – d), where orange shading indicates flow and the grey shading indicates isolated sections of the sample line. The schematics show the series of tests performed to demonstrate that there was negligible effect to measured nvPM brought about by the additional 0.9m stainless steel sample line and splitter. Initial tests were conducted on the 25m sample line connected in sequence directly to the RR or the EU/EASA nvPM systems. After data was taken in the normal AIR6241 configuration, the switching system was added and the measurements repeated so that direct comparison data was available for both the EU/EASA and RR systems with and without the splitter and additional line. The plan was then to repeat this series of tests (4 separate measurements, two by RR and two by EU/EASA) at pre-selected multiple engine test points.

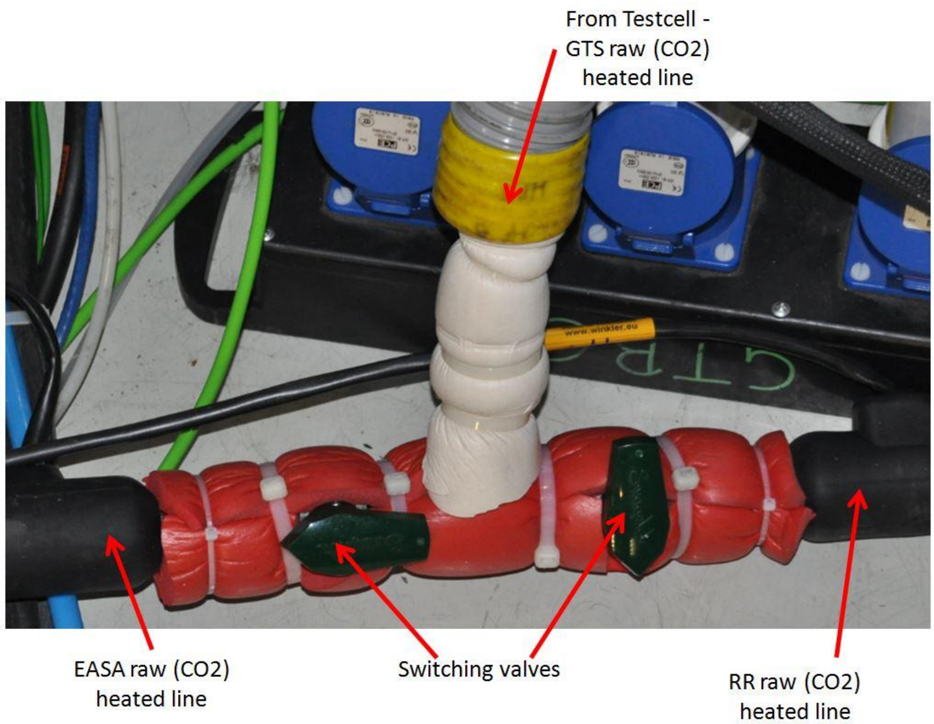
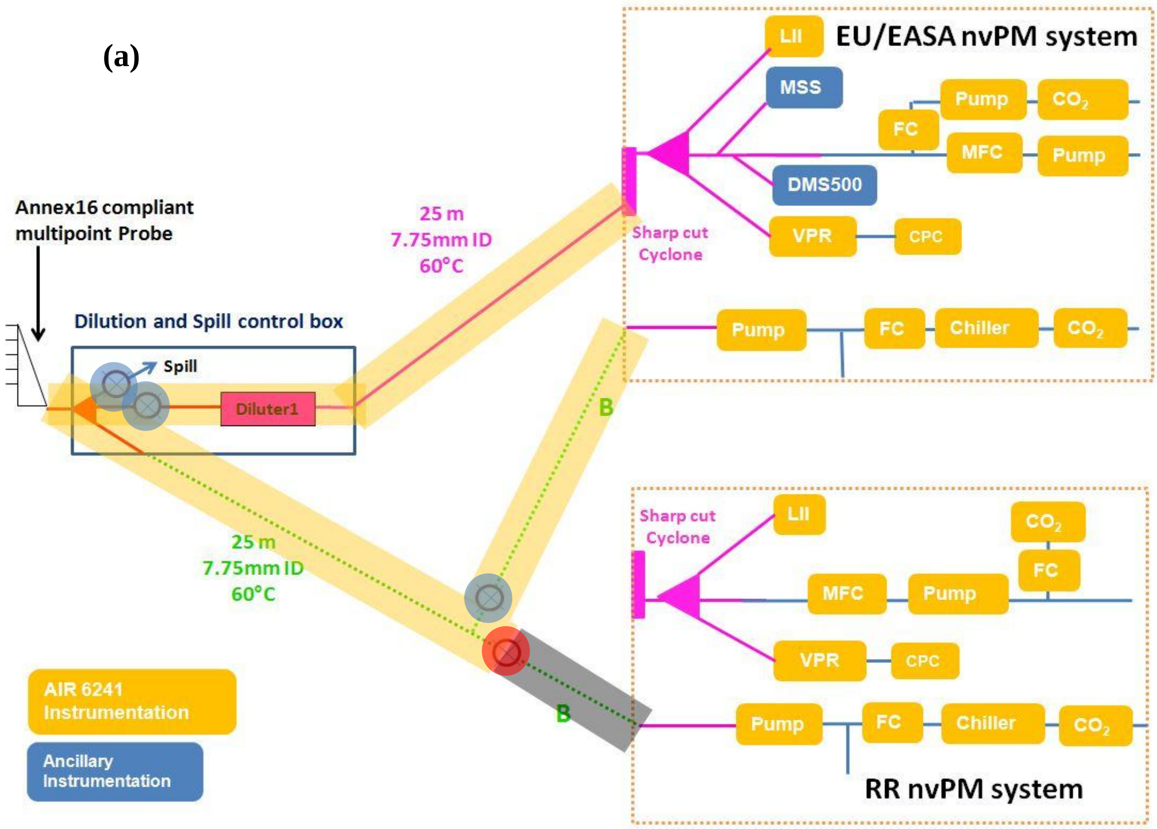
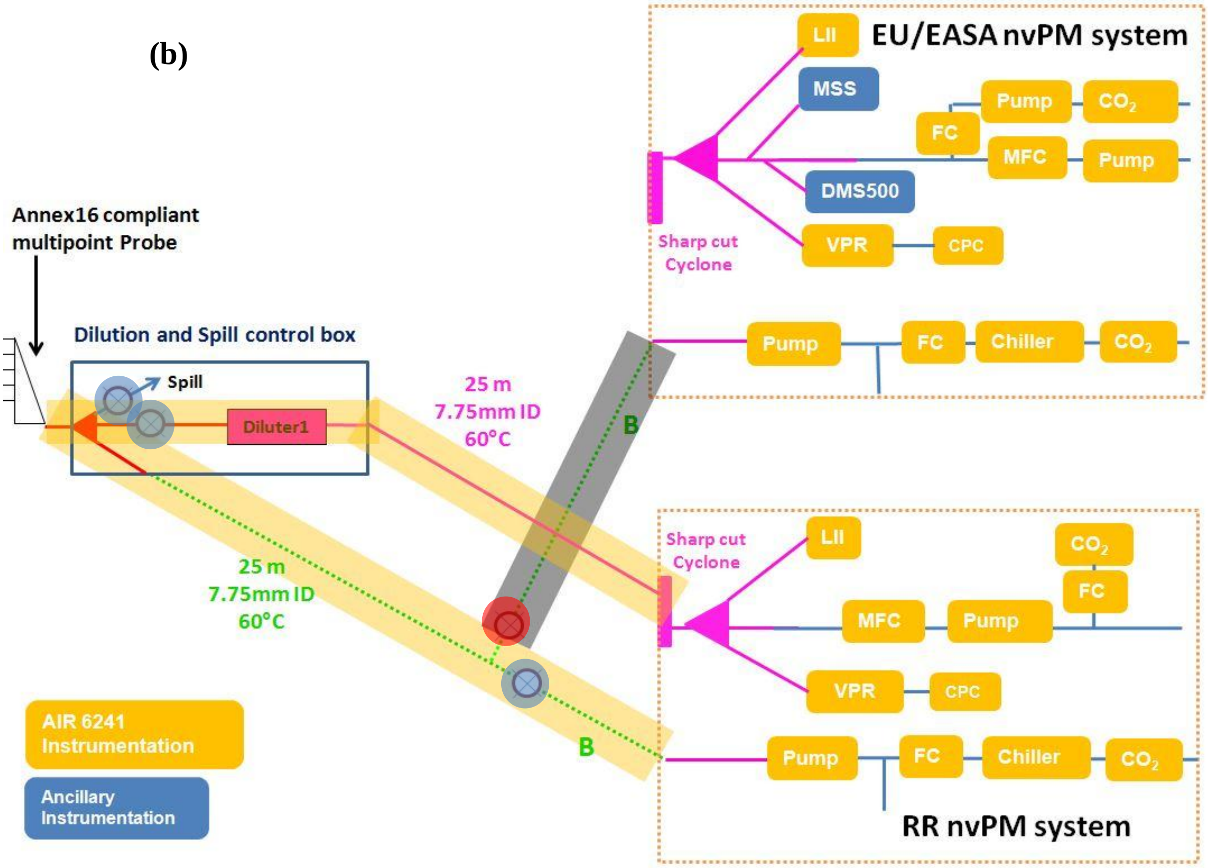


Figure 16 Photograph of GTS switching system

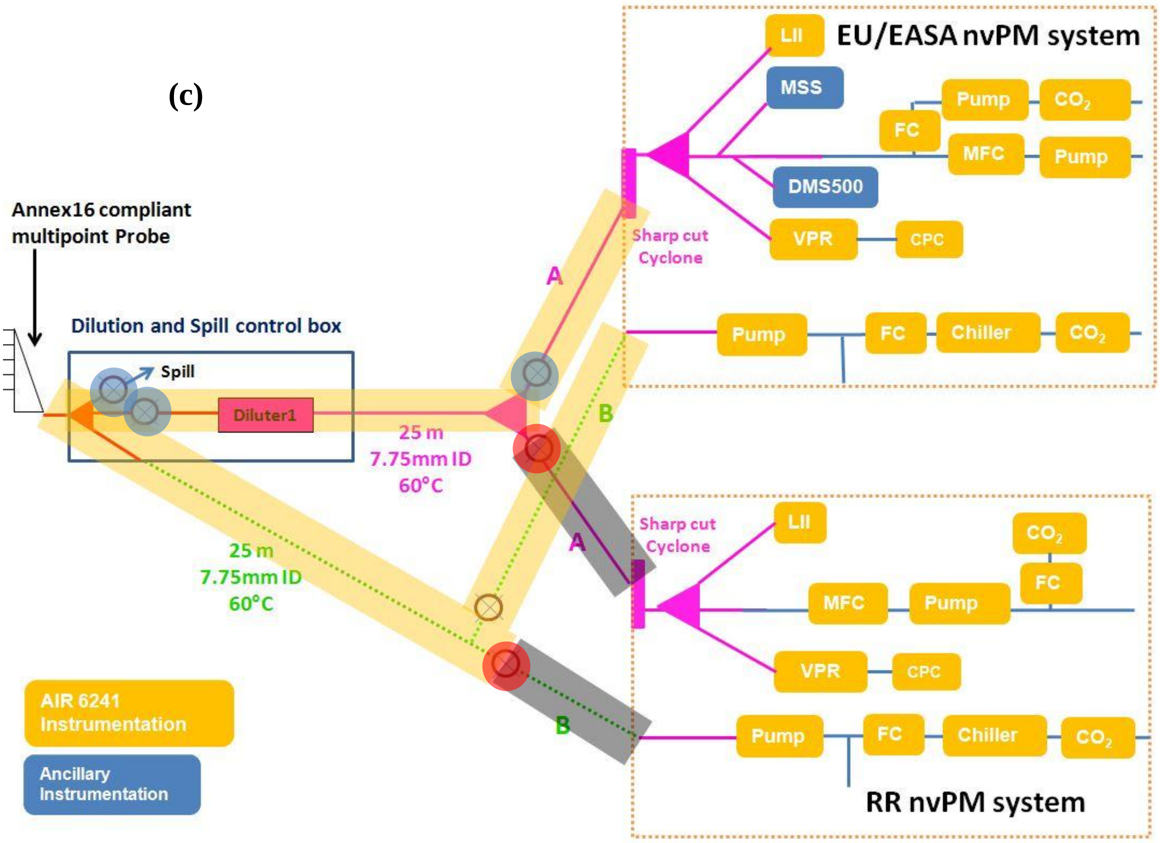
(a)



(b)


EU/EASA nvPM system
LII
MSS
Pump
CO2
FC
MFC
Pump
DMS500
Sharp cut Cyclone
VPR
CPC
Pump
FC
Chiller
CO2
Annex16 compliant multipoint Probe
Dilution and Spill control box
Spill
Diluter1
25 m
7.75mm ID
60°C
B
Sharp cut Cyclone
LII
CO2
FC
MFC
Pump
VPR
CPC
25 m
7.75mm ID
60°C
B
Pump
FC
Chiller
CO2
AIR 6241 Instrumentation
Ancillary Instrumentation
RR nvPM system

(c)


EU/EASA nvPM system
LII
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DMS500
Sharp cut Cyclone
VPR
CPC
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Pump
FC
Chiller
CO2
Annex16 compliant multipoint Probe
Dilution and Spill control box
Spill
Diluter1
25 m
7.75mm ID
60°C
B
Sharp cut Cyclone
A
LII
CO2
FC
MFC
Pump
25 m
7.75mm ID
60°C
VPR
CPC
AIR 6241 Instrumentation
B
Pump
FC
Chiller
CO2
Ancillary Instrumentation
RR nvPM system

(d)

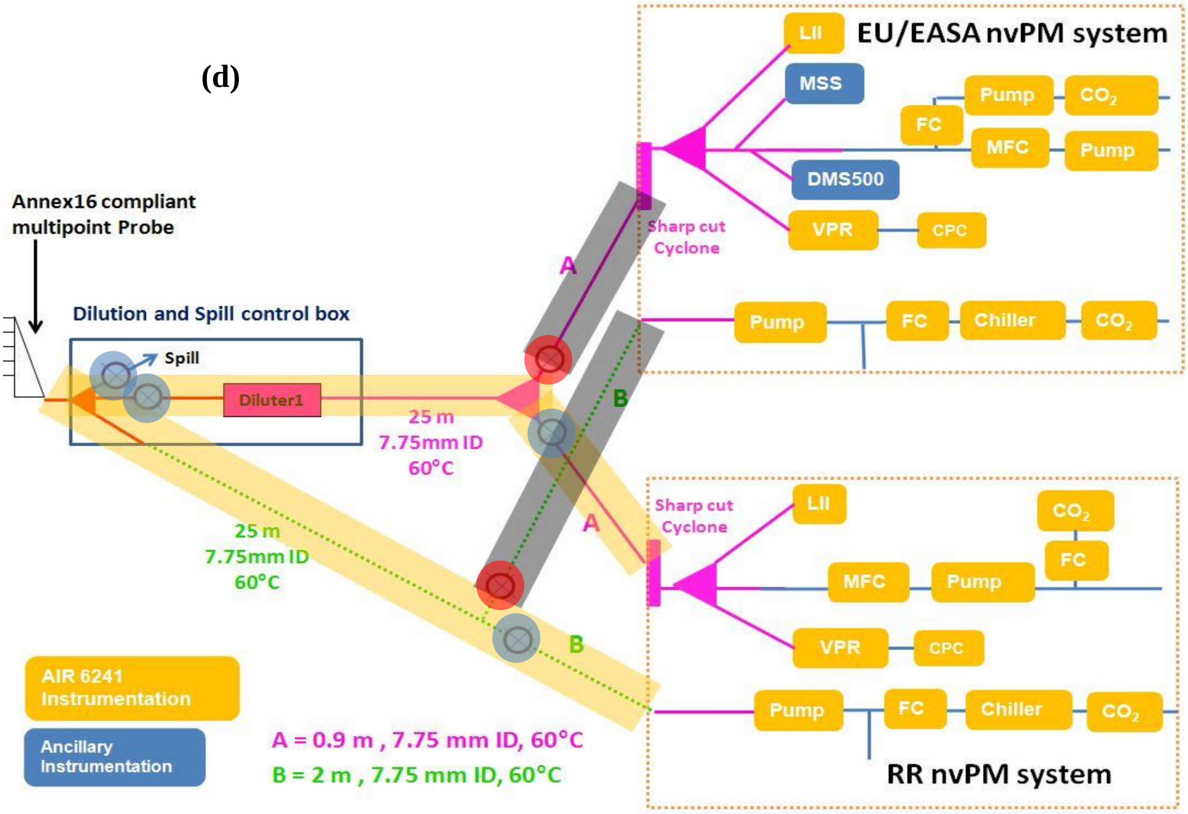

Figure 17 (a-d) System operation schematics – grey shade indicates no flow, orange shade indicates flowing sample. Blue circles indicate OPEN valves, Red circles indicate CLOSED valves. Top schematics (a + b) are 25 m only, Bottom schematics (c + d) are with additional 0.9 m in 4PTS section. EU/EASA measurement is (a + c), RR measurement is (b + d).

6.3.3 Test relevant Certification Records

6.3.3.1 *Zero & Span Gases*

A summary of all of the zero and span gases used in both engine test campaigns is given below in Table 6, with copies of the cylinder verifications presented in Appendix 9.7.

Table 6 Summary of Span & Zero Gases used for both engine test campaigns

Description	Composition	Accuracy	Expiry date
Zero Air	20.90% O_2 (balance N_2)	±0.01%	09/11/2019
Raw CO_2 Span	5.00% (balance N_2)	±0.01%	09/11/2019
1° Diluter CO_2 Span	0.4494% (balance N_2)	±0.001%	13/11/2019

6.3.3.2 *Fuel Analysis*

Rolls-Royce obtained 7 samples of Jet A-1 fuel during the Lean burn staged engine test campaign. Fuel analysis indicated that all samples were identical thus further detailed analysis was only performed on one of the samples. As the engine test was not a certification test not all tests were performed to Annex 16 fuel specifications.

A summary of the results with the Annex 16 specifications are presented below in Table 7 and the individual test certificates are presented in Appendix 9.5.3. It can be seen that where data exists, the fuel composition was within Annex 16 fuel specification. There is no impact for system inter-comparison purposes that the fuel analysis was only partially complete to Annex 16.

Table 7 Summary of measured fuel specifications for fuel used at RR Bristol

Parameter	Unit	Annex 16 LOW	Annex 16 HIGH	Fuel Test
Aromatics	% (V/V)	15	23	17.5
Sulphur, total	% (m/m)	0	0.3	Not measured
Initial boiling point	°C	NA	NA	155
Density at 15 °C	kg/m³	780	820	793.8
Viscosity at -20 °C	mm²/s	2.5	6.5	2.9
Specific energy, net	MJ/kg	42.86	43.5	43.3
Smoke point	mm	20	28	Not measured
Naphthalenes	% (V/V)	1	3.5	Not measured
Hydrogen	% (m/m)	13.4	14.3	14.1
H/C ratio (calculated)	NA	1.84	1.99	1.96

For the in-production rich burn engine test, Jet A-1 fuel was utilised. As the emissions test was not completed fuel samples were not obtained and thus no detailed fuel analysis is available.

6.4 Conclusions of Task 2b

1) Two AIR6241 compliant nvPM systems (RR and EU/EASA) were successfully installed, operated and tested back-to-back on a lean burn staged engine across a wide range of engine power conditions

2) Two AIR6241 compliant nvPM measurement analyser systems (RR and EU/EASA) were successfully installed, operated and tested back-to-back on an in-production rich burn engine at two power conditions.

3) The possibility of installing, and therefore performing, a full sampling system inter-comparison is facility dependent. This will have an impact on the possibility of performing this specific test type in the future. However, different types (as detailed in the report) of system inter-comparison tests are beneficial and advantageous to SAE E31 to further assess and minimise sources of nvPM measurement uncertainty.

7. Task 2c: Data Analysis

7.1 Introduction

The data analysis chapter is split primarily into four sections. The first section describes the system and analyser inter-comparisons for both SAMPLE III SC05 engine test campaigns, detailing AIR6241 compliant nvPM data output and includes operability analysis. The next section details additional particle size and mass measurements obtained on both SAMPLE III SC05 engine test campaigns which are not required for AIR6241. The third section analyses and discusses engine data which is close to the Limit of Detection (LOD) of the instrumentation (mass, number and size). With the final section assessing the use of the SAE E31 draft line loss correction methodology using data from SAMPLE III SC03 (small helicopter engine) and the SAMPLE III SC05 lean burn staged engine; estimating the particle correction factors for mass and number and comparing the mathematically derived pseudo-size distributions with actual measured size distributions.

7.2 System Inter-comparison

To systematically describe the results, they are described in numerous sections as follows: Data Analysis in 7.2.1, where the modus operandi of the data collection and past projects are described; Measurement Data is subsequently presented in section 7.2.2, with Number and Mass data presented; Operational parameters are discussed in section 7.2.3, with conformance and operational variance to AIR 6241 shown; and finally in section 7.2.4 the additional line length comparison in 4PTS conducted during the inter-comparison tests performed at Rolls-Royce Derby are presented.

7.2.1 Data Analysis Procedure

The data points used for analysis conform to AIR6241, namely the nvPM signal was stable before a 30 s average obtained.

Due to engine proprietary data, absolute EI values are not shown. However, these values are not required to facilitate an inter-comparison analysis of the two aforementioned nvPM measurement systems. Where possible generalised EI ranges are given to indicate the wide range of measurements being obtained by the nvPM systems.

Analysis has been performed comparing data obtained within SAMPLE III SC05 (from both engine types; lean burn staged and rich burn) to existing comparison datasets from SAMPLE III SC02 and SC03 data sets. It is important to understand the differences between such datasets so that firm conclusions can be made based upon such analysis as such a description of each campaign highlighting any differences is offered below.

***SC02 data*: Dataset showing AIR6241 sampling system variance**
This dataset was obtained from two sampling and measurement nvPM systems which would have been largely AIR6241 compliant - if the document had existed at the time - with the only non-compliance being that of the Swiss cyclone which exhibited a slightly shallower cut-point curve to that now specified, however it is not expected by the authors that this difference would seriously impact the quoted results.

The 5PTS geometry was identical for both systems and the mass, number and CO_2 analysers were 'set' to be normalised to each other (the purpose of this experiment was to understand sampling system variability rather than analyser variability), and so were not calibrated to AIR6241 specification.

The nvPM systems were operated in a manner which was compliant to AIR6241 however, the primary dilution factor of one of the systems was higher than the AIR6241 prescribed range reaching levels of up to 18 compared to the allowable upper limit of 13. The sampling probe was single point and placed in the core flow behind a fairly modern in-service engine CFM56-5B4-2P operated from idle to maximum thrust, with nvPM measurements obtained simultaneously on both systems.

SC03 data: **Dataset showing AIR6241 nvPM system (sampling + instruments) variance**
Data obtained on two AIR6241 compliant nvPM systems.
The probe was again single point and placed in core flow behind a fairly modern in-service engine CFM56-7B operated across ICAO LTO conditions, with nvPM measurements obtained simultaneously on both systems

SC05 Lean burn staged data: **Dataset showing AIR6241 nvPM system (sampling + instruments) variance**
Data obtained on two AIR6241 compliant nvPM systems.
The probe was multi-point and shown to representative sampling behind a modern engine in the core flow, with the engine operated across idle to maximum thrust conditions, with nvPM comparison measurements being conducted sequentially (immediately with no change in engine condition)

SC05 In-Production Rich burn data: **Dataset showing AIR6241 nvPM instrument variance**
Data obtained with two AIR6241 compliant nvPM measurement systems sampling on a single AIR6241 compliant sampling system.
The representative probe was ICAO Annex16 compliant and placed behind a modern in-production engine in the core flow, with the engine operated at low power conditions only,
nvPM measurements were obtained sequentially (immediately with no change in engine condition)

7.2.2 Measurement comparison

To facilitate an easier interpretation of the results n umber and mass results are summarised separately in sections 7.2.2.1, and 7.2.2.2 respectively.

7.2.2.1 *nvPM Number Measurement on RR lean burn staged engine*

Using the lean burn staged engine data a comparison of nvPM number Emission Index (EInum) between the EU/EASA and RR systems across the engine power range is shown below in Figure 18. Two distinct EI levels are observed which directly relate to the engine mode of operation: the pilot only mode (similar to in-production rich burn combustor operation), available at low engine power; the staged mode, for higher engine power. The Emission Index increased with the engine power as expected, until the switch to the staged combustion mode, where there was a four order of magnitude decrease in results – such that the measured EInum is within the Limit of Quantification and close to the equivalent engine inlet ambient level (both defined below).

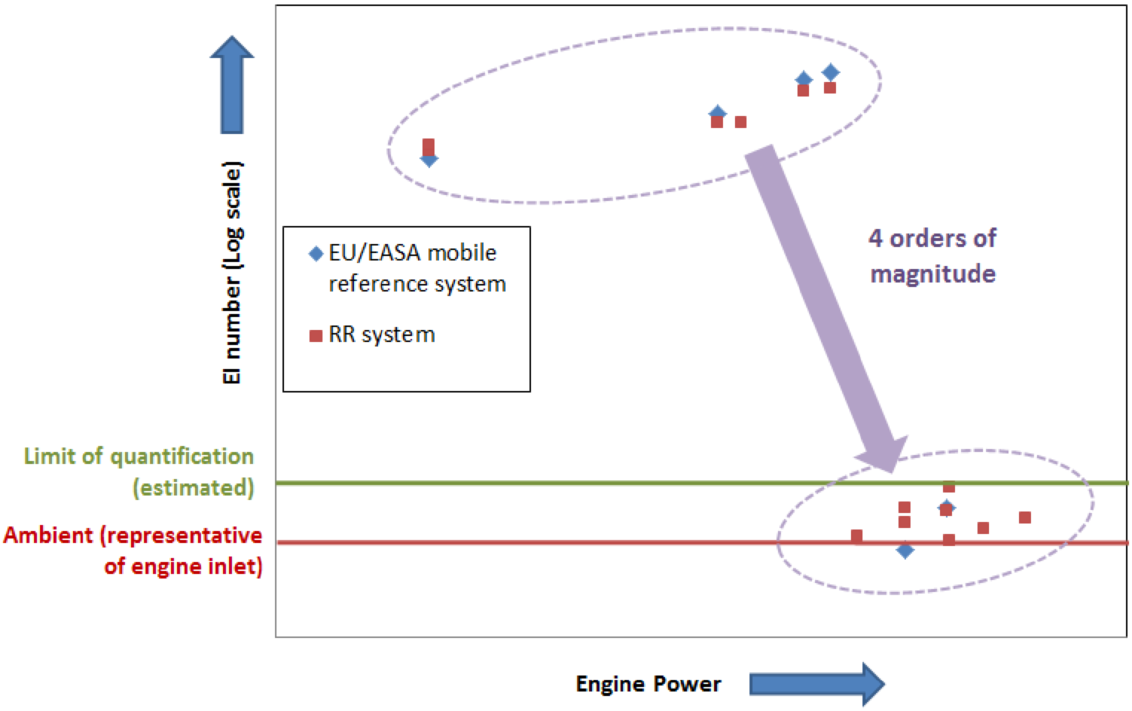

Figure 18 Lean burn staged nvPM number measurements across the engine power range

The green line is an estimation of the Limit of Quantification (LOQ) level:
An estimation of the lowest quantifiable (uncertainty within ±25 %) engine exhaust nvPM measurement. This level is based upon an estimation of where the measurement variability increases above the SAE E31 reported ±25% (CAEP10-WG3-PMTG4-WP03). Note that LOQ is not equivalent to instrument Limit of detection (LOD).

The red line represents the ambient particle concentration level as measured via AIR6241 procedures:
A calculation of engine EI based upon the measured (representative of engine inlet) ambient nvPM concentration. (It is approximated here to a single EI value but is dependent on engine condition). The level will vary for each specific engine test depending upon local background nvPM pollution concentration.

Note that having the engine LOQ above the ambient level is not inconsistent because the ambient nvPM measurement is obtained without primary dilution and over a longer sample averaging period (3 minutes vs 30 seconds).

Both nvPM systems correlate together across the pilot only mode power range. For the staged mode there is a higher variability between the results. However, this is to be expected as the EInum measurements are below the LOQ (and therefore have higher uncertainty) and in addition the raw CPC concentrations are well below the traceable calibration range (approx. 1e3 P/cm^3) – it is unknown whether either CPC measurement uncertainty is within ±10 % (as discussed previously in Figure 7).

More detailed system comparison analysis for the lean burn engine pilot only mode and the in-production engine data is shown in Figure 19 and also evaluated against other SAMPLEIII system comparison datasets (as explained in 7.2.1). The data is plotted against the average of the two nvPM systems as neither system is assumed to be measuring the actual true concentration given the estimated uncertainties associated with calibration and measurement. The SAE E31 25 % current estimation of nvPM system variability is also drawn on the figure. It can be observed that all the EInum comparison data is within the estimated variability band, which gives confidence to the AIR as the type of number instrumentation (VPR & CPC) used in RR system is not identical to the EU/EASA system, as has been the case in all previous test campaigns. All the system comparisons are fairly consistent across the EInum range across a range of engines and power conditions. The analyser comparison (blue triangles) shows much better agreement (within ± 6%) than the full system comparison (±10 to 20 %), this is not surprising as the 3PTS and 4PTS sampling system variability is removed from this dataset.

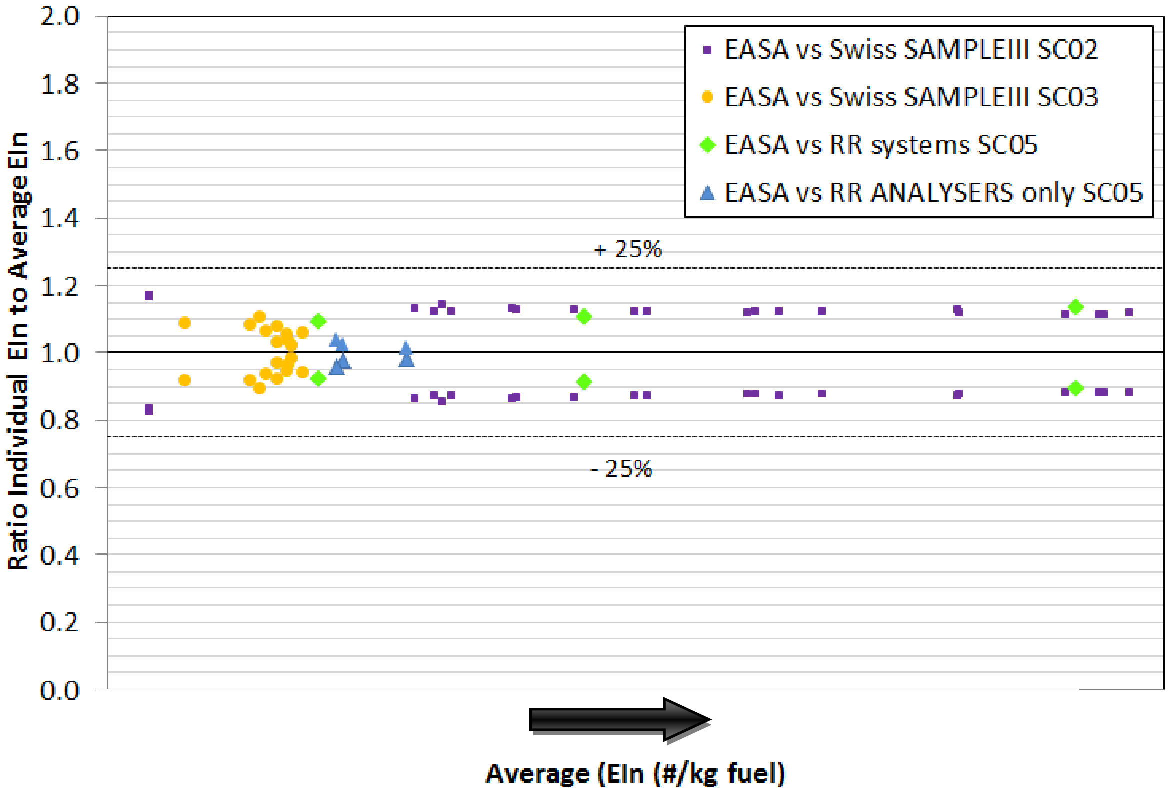

Figure 19 Inter-comparison of EIn variability between multiple AIR6241 nvPM systems on different engine test campaigns (lean burn engine pilot mode and in production rich burn engine data)

In Figure 20 the lean burn staged data is added for comparison (note that the x-axis is now a log scale to enable clear viewing of the data). It is observed that the majority of the staged data is outside the estimated ±25 % variability limit and this is due to the very low number concentrations being measured by the CPC. More system comparison data would be needed between the two data regimes to assess and determine at what concentration the EInum measurement increases above the estimated ±25 % variability band.

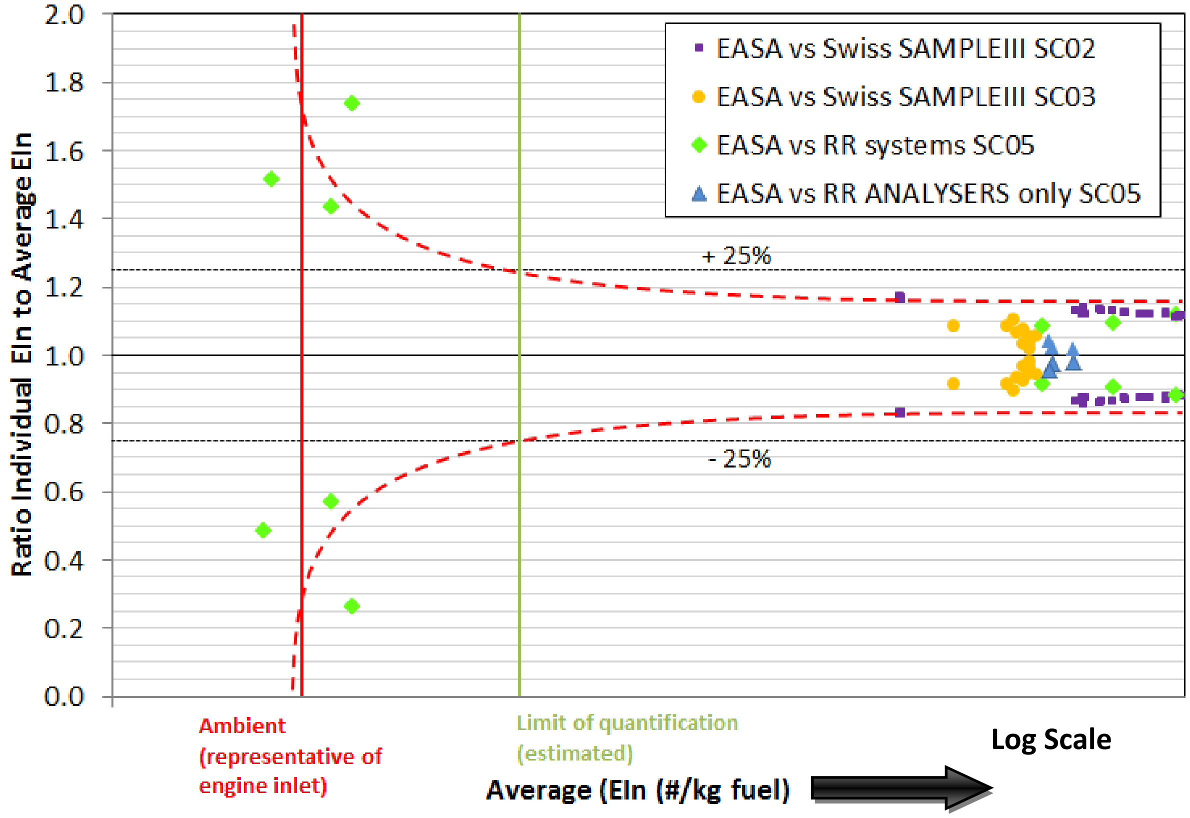

Figure 20 Inter-comparison of EIn variability between multiple AIR6241 nvPM systems on different engine test campaigns with logarithmic x-axis including lean burn staged data, ambient and LOQ levels. Dotted red curve shows an estimated trend representation of system inter-comparison data.

7.2.2.2 *nvPM Mass Measurement on RR lean burn staged engine*

A comparison of the RR and EU/EASA nvPM systems mass Emissions Index (EImass) across the lean burn staged engine power range data is shown below in Figure 21; the EImass again showed two distinct levels which directly relate to the engine mode operated. The pilot only mode (similar to in-production rich burn combustor operation) showed approximately three orders of magnitude difference in EImass to the staged mode (used in the higher engine power). The pattern is the same from the number EI: at low power the engine is in pilot only mode; as the engine power increases so does the EImass; then the engine switches to staged mode where the EI drops dramatically to within the LOQ and close to the equivalent engine inlet ambient level (repeated below).

The green line is an estimation of the Limit of Quantification (LOQ) level:
An estimation of the lowest quantifiable (uncertainty within ± 25%) engine exhaust nvPM measurement. This level is based upon an estimation of where the measurement variability increases above the SAE E31 reported ± 25% (CAEP10-WG3-PMTG4-WP03). Note that LOQ is not equivalent to instrument Limit of detection (LOD).

The red line represents the ambient particle concentration level as measured via AIR6241 procedures:
A calculation of engine EI based upon the measured (representative of engine inlet) ambient nvPM concentration. (It is approximated here to a single EI value but is dependent on engine

condition). The level will vary for each specific engine test depending upon local background nvPM pollution concentration.

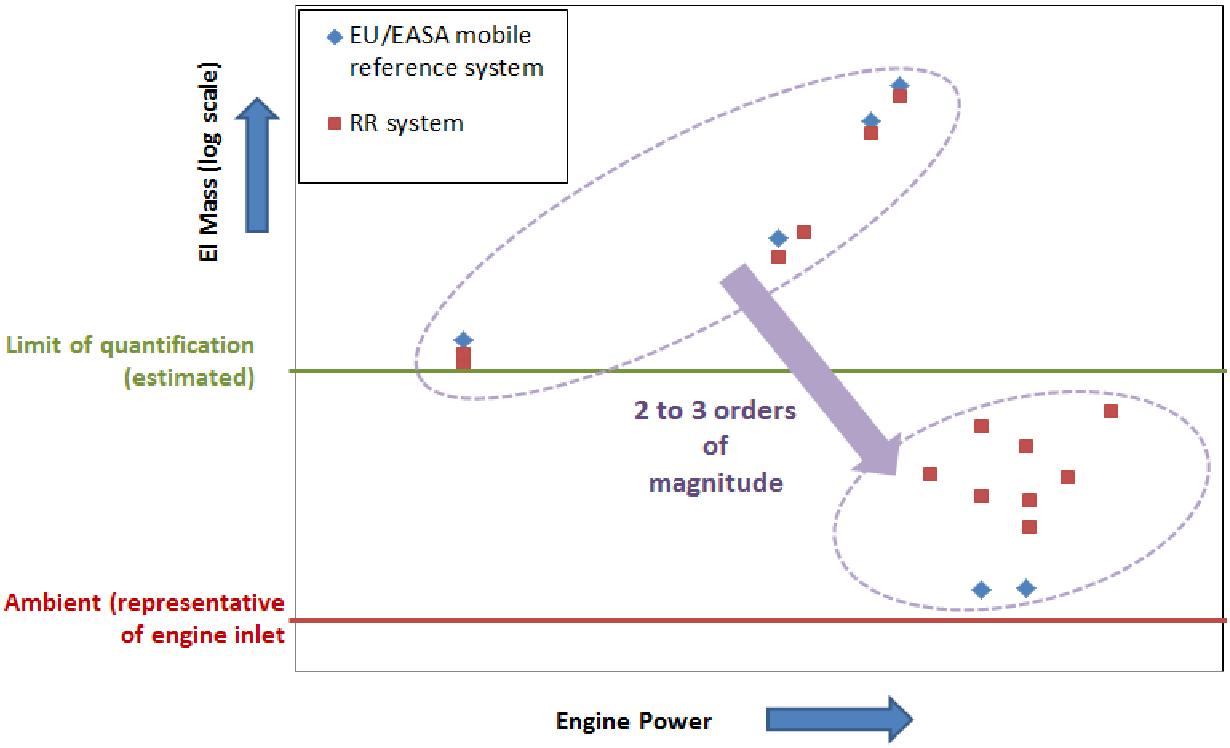

Figure 21 Lean burn staged nvPM mass measurements across the engine power range

Note that having the engine LOQ above the ambient level is not inconsistent because the ambient nvPM measurement is obtained without primary dilution and over a longer sample averaging period (3 minutes vs 30 seconds).

Both nvPM systems correlate together across the pilot only mode power range. For the staged mode there is a higher variability between the results. However, this is to be expected as the EImass measurements are below the LOQ (so have higher uncertainty) and in addition the raw mass concentrations are below the traceable calibration range.

More detailed system comparison analysis for the lean burn staged engine and the in-production rich burn engine data is shown in Figure 22 and also evaluated against other SAMPLEIII system comparison datasets (as explained in 7.2.1). The data is plotted against the average of the two nvPM systems as again neither system is assumed to be measuring the actual true concentration due to uncertainties associated with calibration and measurement. The SAE E31 ±25 % current estimation of nvPM system variability is also shown. It can be observed that the majority of the EImass comparison data is within the estimated variability band and is consistent with other system inter-comparison datasets. The solid red curve on the graph indicates the shape trend of the APRIDE-4 inter-comparison dataset between the North American and Swiss nvPM systems using the CFM56-5B4-2P engine[a]. This dataset is

[a] Lobo, P. et al, "Measurement of Aircraft Engine Non-volatile PM Emissions: Results from the Aviation - Particle Regulatory Instrument Demonstration Experiment (A-PRIDE) 4 Campaign", *manuscript in preparation to be submitted to Atmospheric Environment (November 2014)*

also consistent with the SC05 comparison datasets, as the EImass decreases towards the mass instrument LOD the spread of data increases above the estimated ±25 % variability.

The analyser comparison (blue triangles) shows better agreement (within ± 9%) than the full system comparison (~± 20% for same EImass level), this is not surprising as the 3PTS and 4PTS sampling system variability is removed from this dataset. It can be observed that at higher EImass, the variability between systems is reduced to be within ± 10%.

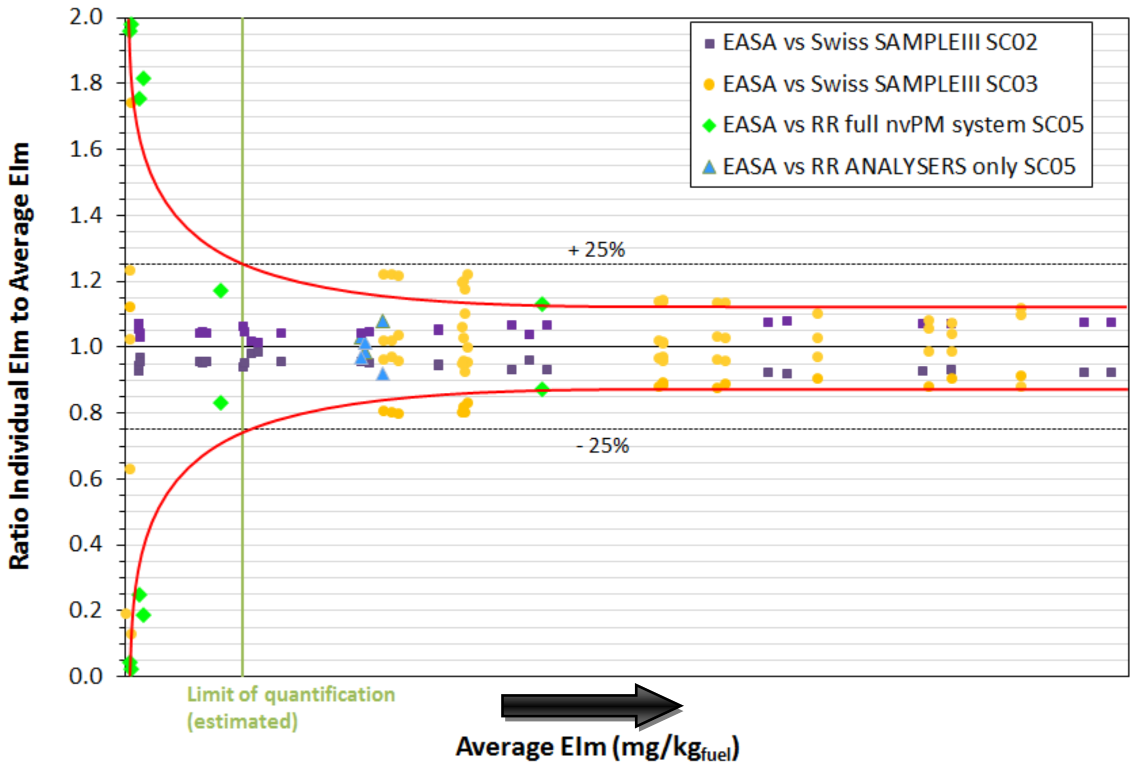

Figure 22 Inter-comparison of EIm variability between multiple AIR6241 nvPM systems on different engine test campaigns including estimation of a possible LOQ

7.2.3 Limit of Quantification Calculation

It can be seen that the absolute variability of EImass and EInum is dependent upon the EImass and EInum data level. It is not constant at low EImass values on rich and lean burn staged engines or at low EInum values on the lean burn staged engine. The red 'trumpet shape' pattern, shown above in the EImass and EInum system comparison Figures, is characteristic of data where the responses standard deviations trend with concentration. The adequacy of the ± 25% uncertainty level depends upon the needs of ICAO in setting a regulatory standard for nvPM. In order to understand the adequacy, it is important to understand what is the lowest Emission Index that can be accurately measured within the uncertainty level. It is this level which is defined in this report as Limit of Quantification (LOQ).

Figure 23 shows the trend between the standard deviation (in this case 2 sigma in order to obtain a 95 % confidence interval) and the EImass calculation. The standard deviation is calculated across the 30 s average measurement. By placing a fit through this trend it is possible to 'read off' where the 2σ trend crosses an acceptable uncertainty allowance.

Currently SAE E31 has estimated 25 % and CAEP WG3 has accepted for the time being this allowance as a first step to work with, this is shown by the red line. The lowest acceptable limit of EImass measurement can therefore be calculated where these two lines cross, this is defined here as Limit of Quantification (LOQ).

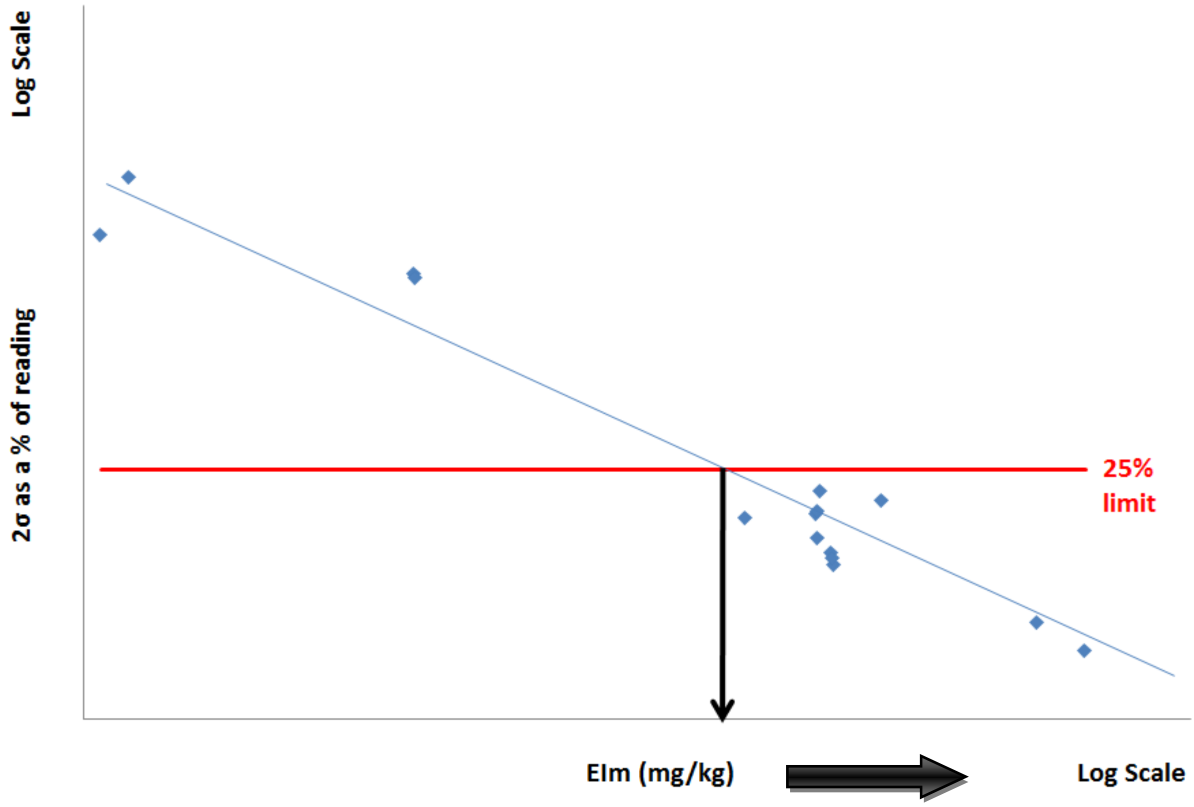

Figure 23 LOQ calculation for EImass measurement using 95% confidence interval (2σ) with acceptable 25% measurement variability limit for the lean burn engine pilot only and staged data. Note both scales are logarithmic

The same analysis can be performed for the EInum calculation. Figure 24 below, shows the trend between the standard deviation (in this case 2 x σ in order to obtain a 95 % confidence interval) and the EInum measurement. Again by placing a fit through this trend it is possible to ‘read off’ where the 2σ trend crosses an acceptable uncertainty allowance. The currently SAE E31 estimation of 25 % (which CAEP WG3 has accepted this allowance), is shown by the red line. The lowest acceptable limit of EInum measurement can therefore be calculated where these two lines cross, this is defined here as Limit of Quantification (LOQ).

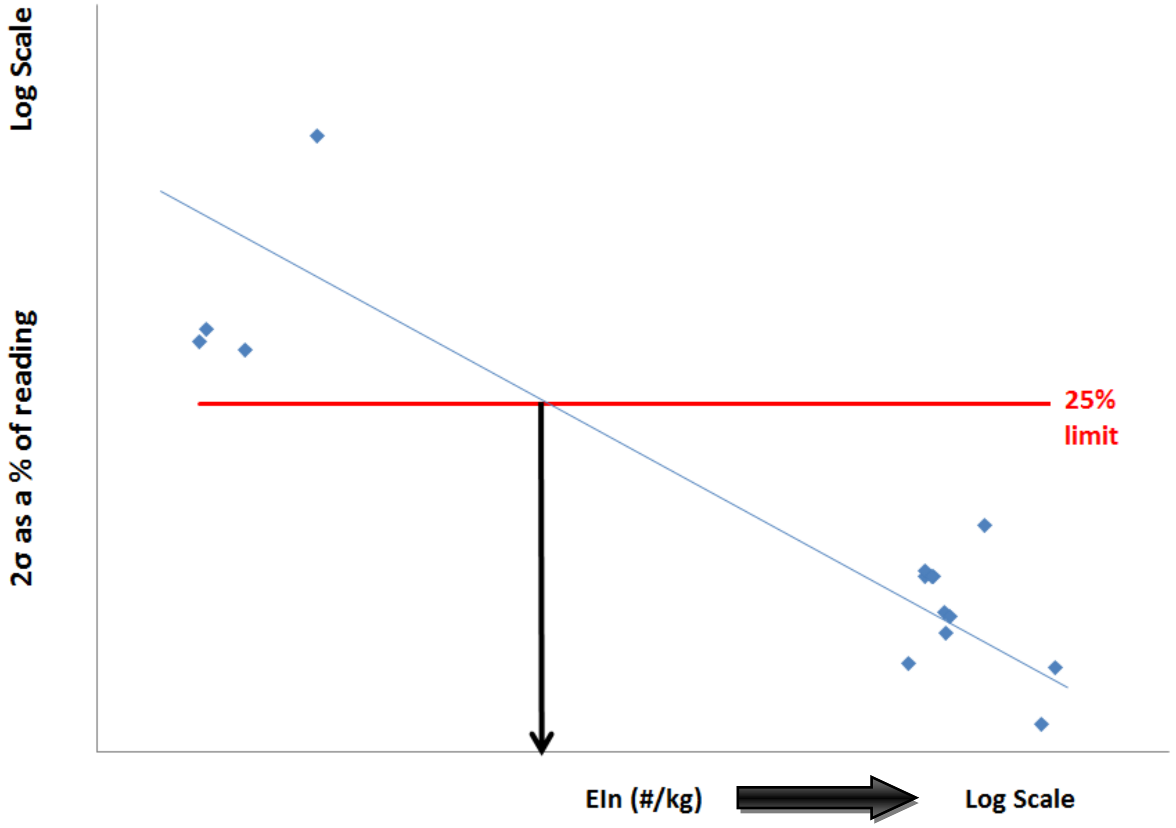

Figure 24 LOQ calculation for EInumber measurement using 95 % confidence interval (2 sigma) with acceptable 25 % measurement variability limit for the learn burn staged engine data. Note both scales are logarithmic.

As further nvPM engine datasets are obtained, it is recommended that 2σ deviation should be reported with any AIR6241 nvPM data point to corroborate the 2σ trend across multiple engine type sources and rake systems. In addition, statistical normality tests should be performed on individual data points as well as testing repeated data points. Thus enabling a calculation of LOQ to be conveyed for regulatory standard setting.

7.2.4 Operational comparison

For AIR6241 operational requirements, both nvPM systems were operated in compliance (e.g. system flowrates, temperatures and pressures). Both systems met the number and mass zero check (<3 µg/m^3 and <1 P/cm^3) and ambient check.

The wide range of lean burn staged engine conditions challenged both nvPM systems to operate under a range of different 2PTS outlet pressure conditions. A comparison of how the primary diluters (in 3PTS) performed in terms of Dilution Factor (DF1) is shown below in Figure 25.

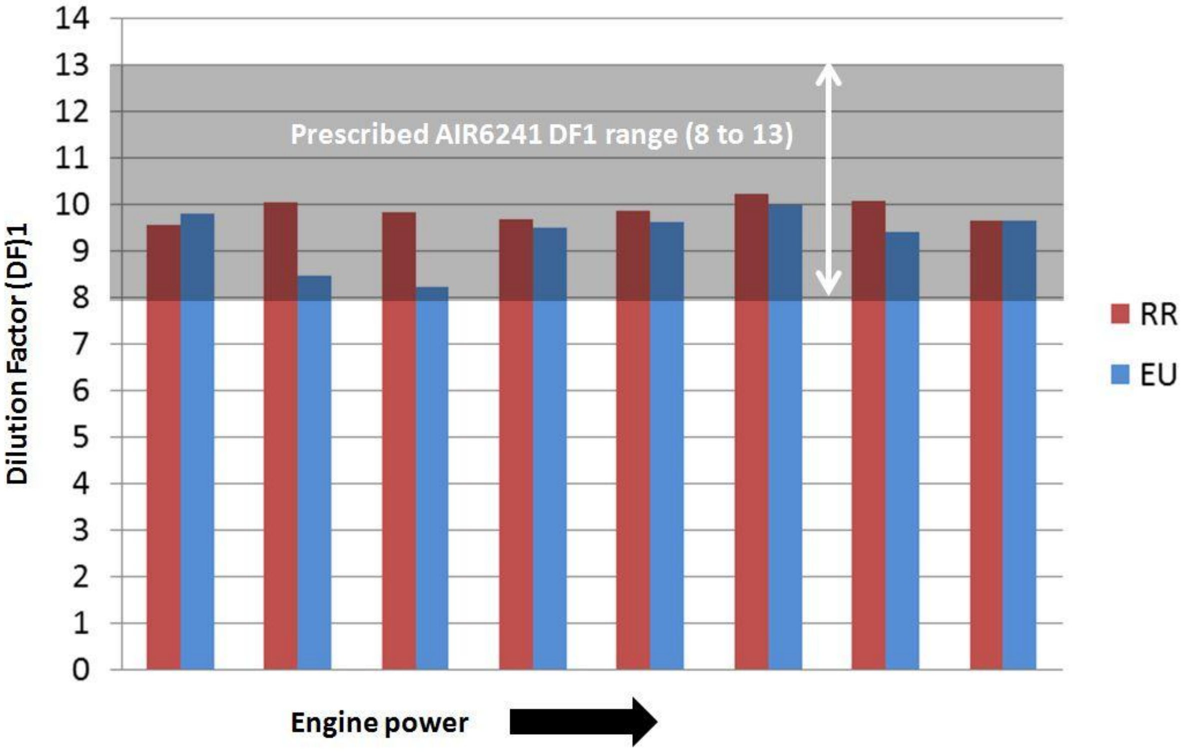

Figure 25 DF1 operation comparison

It can be observed that DF1 for both nvPM systems complies with the AIR6241 allowable range across the entire engine power range. The RR DF1 stays fairly consistent around 10±0.5, whereas the EU/EASA system has slightly more variability (around 8 to 10). The primary dilution factor consistency is dependent on the diluter inlet pressure. In Figure 26 the dependency of primary dilution factor on diluter inlet pressure is shown (note that this is consistent with similar data shown in SAMPLEIII SC02).

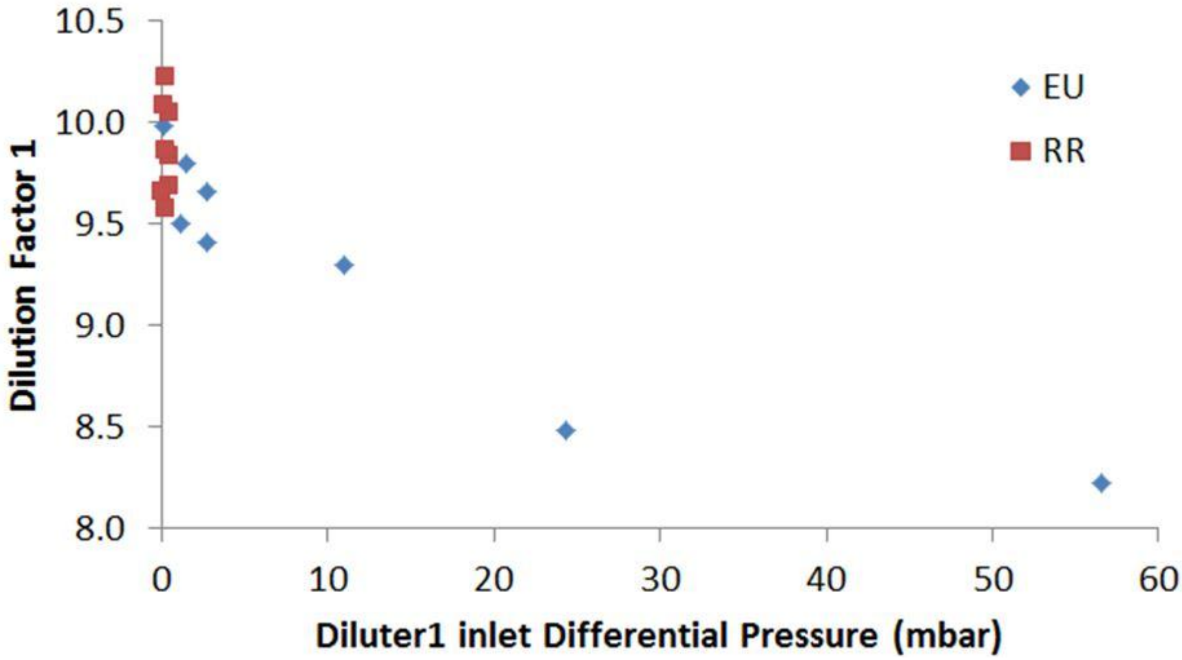

Figure 26 Diluter1 inlet pressure operability comparison

As the diluter inlet pressure increases above the test cell ambient value for the EU/EASA system (occurs as engine power condition increases), the primary dilution factor decreases. For the RR nvPM system the same relationship would be observed, however, the RR spill system geometry is capable of discarding more of the sample flow. Hence the RR system is able to maintain the diluter inlet pressure close to ambient across the entire engine power range and therefore keep the dilution factor fairly constant.

For both nvPM systems the CO_2 gas analyser channels were spanned and zeroed within every hour during test, in accordance with ARP1256. Because of the different dilution factors witnessed between the nvPM systems it is not possible to compare the diluted CO_2 measurements for variability (which are used to calculate the EI's). However, in order to get an understanding of what typical variability is observed in CO_2 measurement, below in Figure 27 a comparison of the two raw CO_2 measurements taken on both nvPM systems is shown.

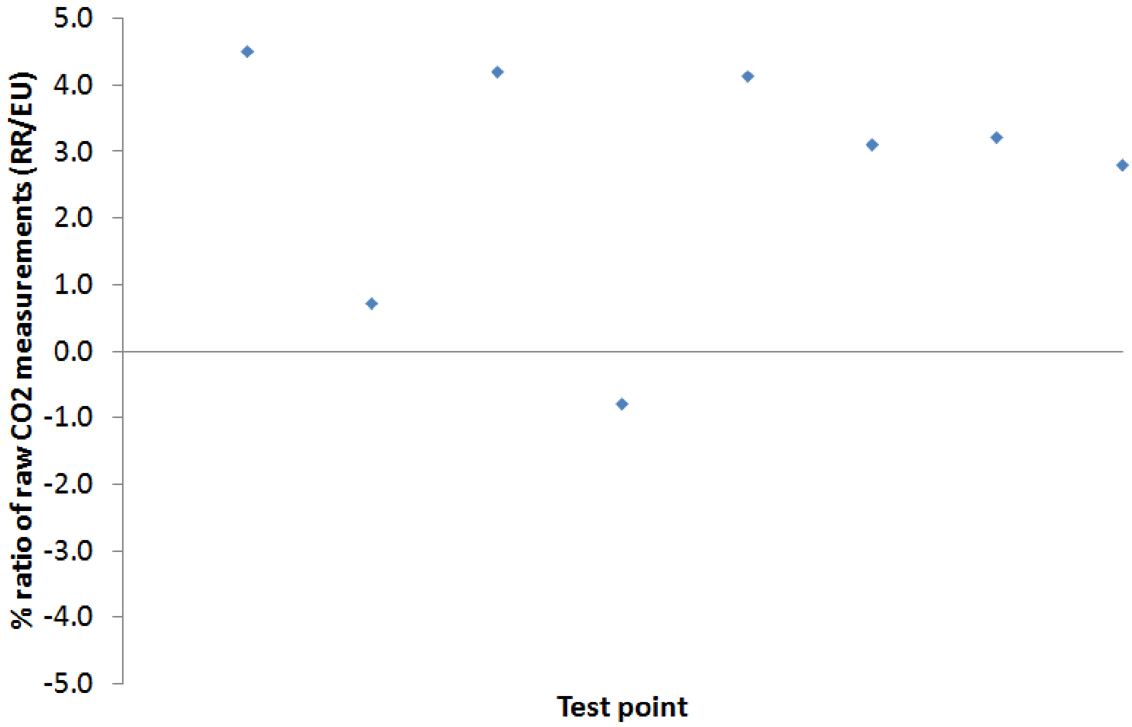

Figure 27 CO_2 measurement variability

Generally there is a systematic bias between the analysers with the RR analyser measuring around 4 % higher than the EU/EASA analyser. At two of the test points the analysers are in much closer agreement. The span and zero calibrations were not time synchronised between the two systems, therefore there will be drift between the two CO_2 measurements.

The bias of the CO_2 analyser is an important component of the EI uncertainty analysis. For example if the RR diluted CO_2 channel also had a systematic positive bias of 4 % (compared to the EU/EASA measurement) then this would directly account for 4 % of the difference observed in the EI system inter-comparison analysis for both mass and number. These differences are acceptable within ARP 1256 performance specifications and similar data was observed in SAMPLE III SC03 between the Swiss and EU/EASA raw CO_2 measurements.

On a steady state engine condition, an experiment performed varying PCRF values and therefore dilution factors. PCRF values of 100 or 250 were requested on the APC and the number concentration values were recorded (shown as a 30 s rolling average to smooth out the data) and corrected for the internal dilution factor based on the dilution checks made in Section 5.4.1.3. The sampled flow rate, mass flow of the dilution spill and the internal pressure among other operational parameters were constant over the measurement periods.

An unexpected average 10 % positive difference step-change is initially observed when using different PCRF factors. From the AVL APC certificate (Appendix 9.5.1) it can be seen that the particle penetration factors do differ between different PCRF settings. And that on average the penetration at a PCRF of 250 is 3% improved compared to the PCRF of 100. This reduces the observed step-change to 7 % but does not eliminate it. Performing the same analysis with the manufacturer dilution factor calibration also shows the same step-change effect though the step narrows to ~6 % and then further to ~3 % (which is within the DF2 measurement uncertainty) taking into account the penetration differences at the two PCRF settings. These differences are shown below in Figure 28.

This might indicate an issue with the CO_2 measurements, but the dilution check results in SAMPLEIII SC05 are consistent with SAMPLEIII SC03 which was performed with a different CO_2 AIR6241 compliant analyser.

The PCRF dilution factor is calibrated and checked with a CO_2 analyser – in AIR6241 the assumption is that the gas path dilution is sufficient to model the particle dilution without taking into account particle penetration losses. This assumption is based on the very small nature of sub-micron PM particles, meaning that Stoke's Law and the drag force exerted by the air is negligible and the particle can behave as a gas and follow gas flow.

This analysis shows that the ± 10% uncertainty in DF2 is not an underestimation and that to reduce variability in EInum, particle dilution is a source of uncertainty to concentrate upon. Potentially the DF2 calculation could include normalisation to account for VPR penetration differences at different dilution settings which could reduce the uncertainty in DF2. The nvPM line loss correction SAE document being developed will correct for VPR penetration differences. However, it has not yet been established what the uncertainty of using this correction is (due to the large dependence on particle size distribution). If the uncertainty of this correction is >10 %, then there is no improvement on using the AIR6241 methodology for a standardised methodology purpose.

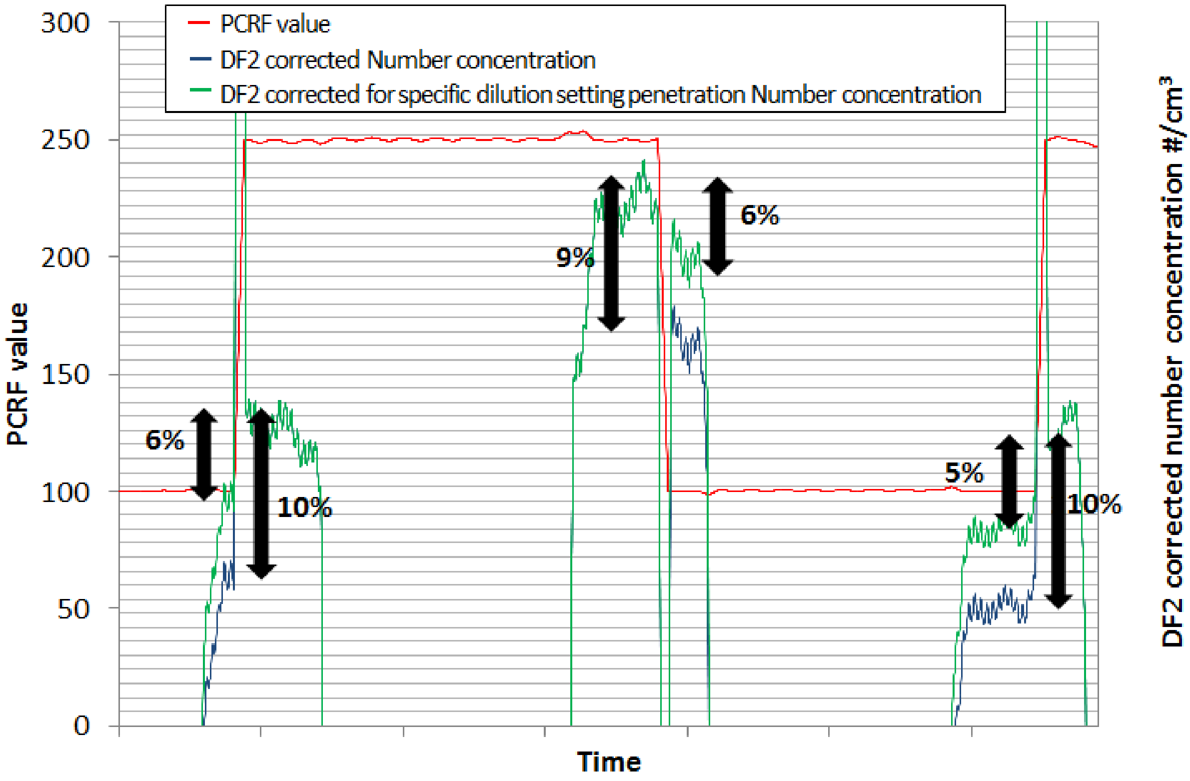

Figure 28 DF2 VPR setting variance corrected for differences in average VPR penetration at the different engine power settings (presented data is a 30s rolling average)

7.2.5 Additional 4PTS line length comparison

For the operational setup on the in-production rich burn engine test it was required to assess the impact of adding a splitter and 0.9 m length of sampling line at the end of 4PTS (as shown in Figure 17).

Theoretically the UTRC model predicts <1 % impact on the number measurement for the additional line length, and <<1 % for the mass measurement.

A comparison of the adding the extra line length on both the EU/EASA and RR nvPM systems at two different engine power conditions is shown below in Figure 29 for both number and mass measurements.

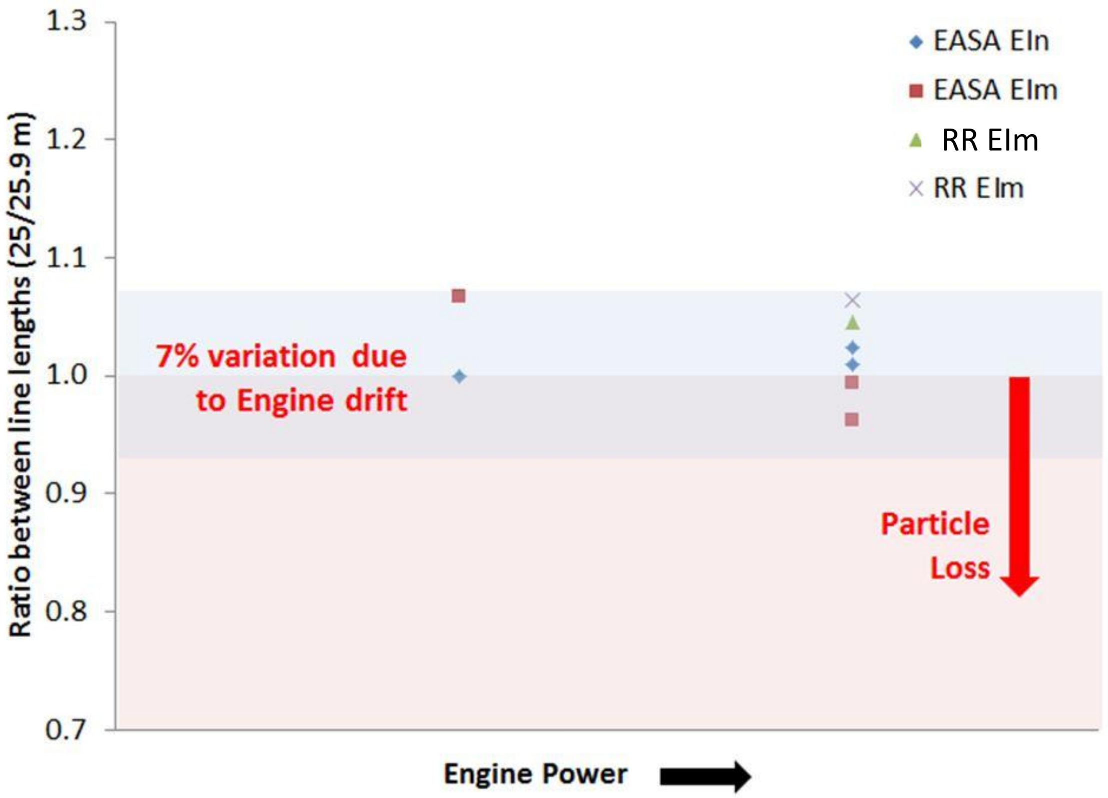

Figure 29 Variation due to additional line length on rich burn engine

It is physically impossible to produce non-volatile particles in a sampling system – they can only be lost via physical processes (apart from random particle shedding events). This is shown by the pink shaded box and red arrow indicating the area where non-volatile particle loss can only occur. It can be observed that at both engine power conditions there is data occurring above and below the ratio of 1 which is physically not possible, thus can only be attributed to engine variation.

Measurements were being obtained on a sequential basis of several minutes across a time period of around 40 minutes (the measurements could not be performed simultaneously). Consequently it appears from the analysis that drift in engine nvPM emissions plus nvPM instrument variability over this time period (~7 % in Figure 29), is much larger than any additional particle loss caused by the extra sampling length. This agrees with the UTRC theoretical penetration assessment, thus indicating that there was negligible impact of the extra 4PTS line length.

7.3 Additional nvPM System data

The opportunity was taken to obtain additional particle size and mass data utilising both 5PTSaux (additional line shown in Figure 30) and the exhaust of the APC. With additional size distribution data presented in section 7.3.1, while the mass results are summarised in section 7.3.2 – the additional instrument allowed for a mass inter-comparison within the EU/EASA nvPM system.

7.3.1 Particle size distributions

Size distributions were measured in the two tests: in the lean burn test, a Scanning Mobility Particle Sizer (SMPS, from TSI) and a Differential Mobility Spectrometer (DMS500 from Cambustion); and in the in-production engine test the DMS500 was utilised in isolation.

The DMS500 was located at the 5PTSaux, as seen in the schematic shown below in Figure 30. The transport penetration difference between the outlets along the 5PTS system within the oven are negligible, further details available in EASA.2010/FC10 SC03.

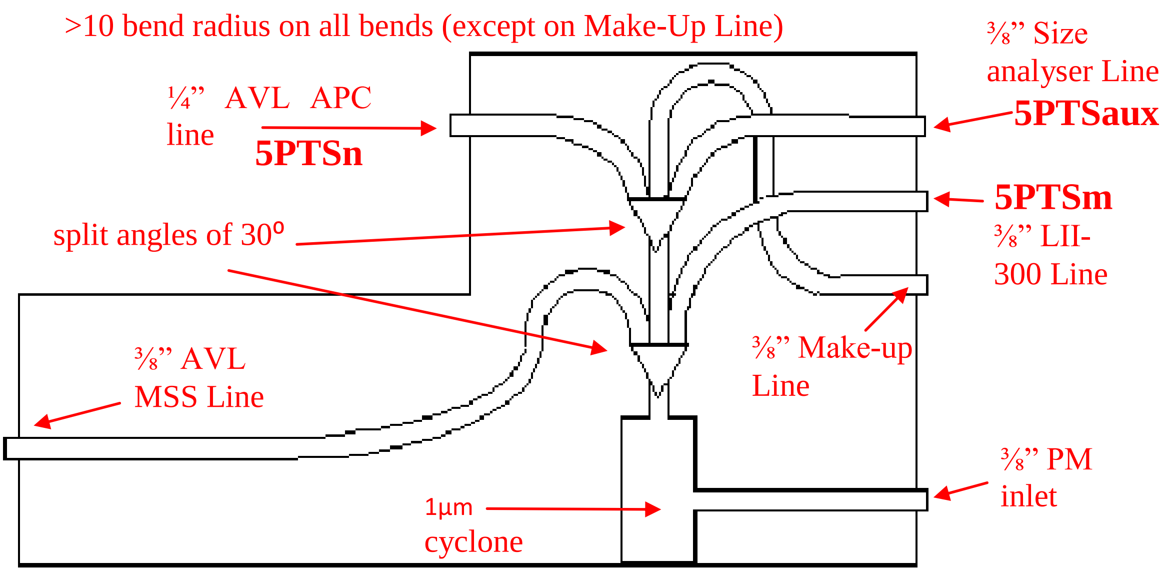

Figure 30 Schematic of 5PTS system within oven to the separate instruments

The SMPS was located at the diluted exhaust of the APC (using a splitter which provided no back pressure to the CPC inside APC) which had the effect of an extra dilution step and additional particle transport loss from the extra pathway and VPR; these losses were corrected (discussed in more detail later in section 7.5.3) to allow direct comparison with the DMS size data.

The raw and fitted SMPS distributions are shown below in Figure 31, which were corrected for DF1 and VPR DF2.

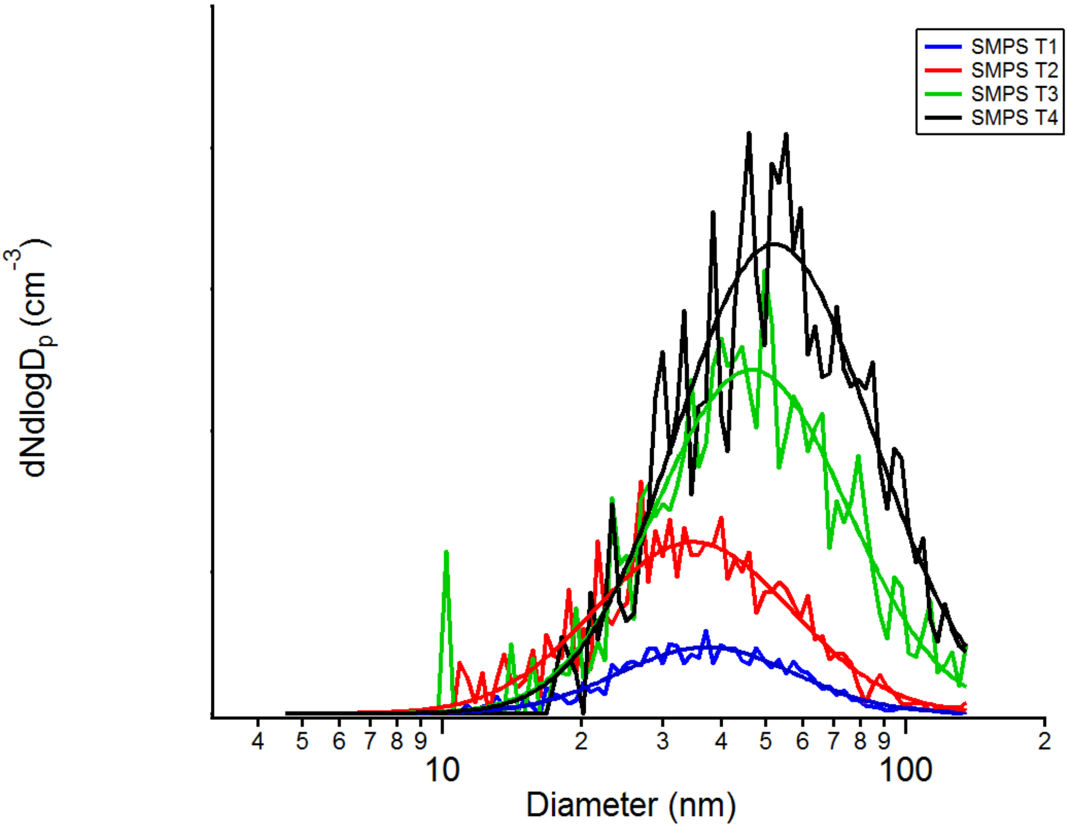

Figure 31 Raw and fitted size distribution graph for the SMPS for the lean burn pilot only conditions T1, T2, T3 and T4 (corrected for DF1 and VPR DF2)

VPR dilution corrected SMPS raw and VPR loss corrected size distributions compared to DMS size distributions are shown below in Figure 32 (a,b,c and d). We observe distinctly monomodal distributions in both the SMPS and the DMS results in all the engine conditions T1 through to T4 – these represented the lean burn engine with pilot only conditions (similar to rich burn). Even using the bimodal DMS500 data inversion probability fit showed a distinctly monomodal bias, reaffirming the result. Once the SMPS data has been corrected for VPR penetration loss, both the SMPS and the DMS show good agreement in geometric mean diameters (DGN), with the DMS recording 35.2 nm, 34.1 nm, 45.1 nm and 48.7 nm respectively for the four engine powers and in comparison the SMPS measured 34.3 nm, 30.6 nm, 43.9 nm, and 49.7 nm giving an average deviation between the two instruments of less than 4 %. In addition the DMS recorded geometric standard deviations (GSD) of: 1.53, 1.60, 1.57 and 1.55 for test cases T1 through to T4 respectively.

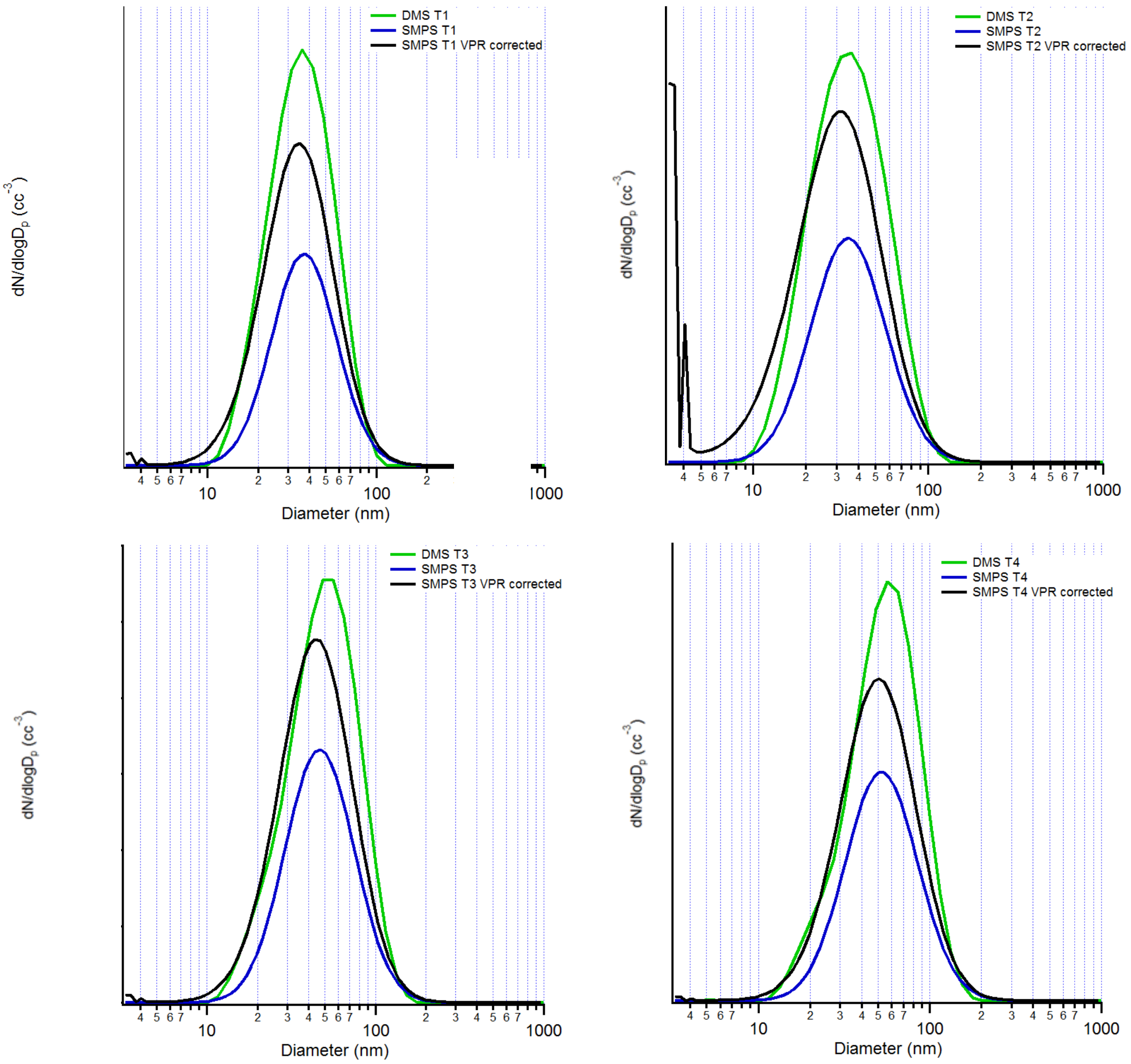

Figure 32 (a-d) Size distribution graphs for the DMS and SMPS and SMPS corrected for DF2 lean burn engine conditions T1, T2, T3 and T4. SMPS Tx VPR corrected is the predicted SMPS distribution upstream of the VPR, after the VPR loss function has been applied.

In the lean burn staged engine conditions T5, T6, T7 and T8, both the SMPS and the DMS showed much reduced detection capability. The SMPS recorded a noisy zero signal and the DMS was also close to its limits of detection. This is discussed further in section 7.4.

For the large in-production rich burn engine test, two test points P1 and P2 were obtained with and without the 0.9m extension to prove that the difference was negligible, as can be seen below in Figure 33. Again it is observed that the extra 0.9m length of line is causing a negligible (below limit of measurement uncertainty) additional loss in PM across the observed size range in agreement with earlier EInum & mass data.

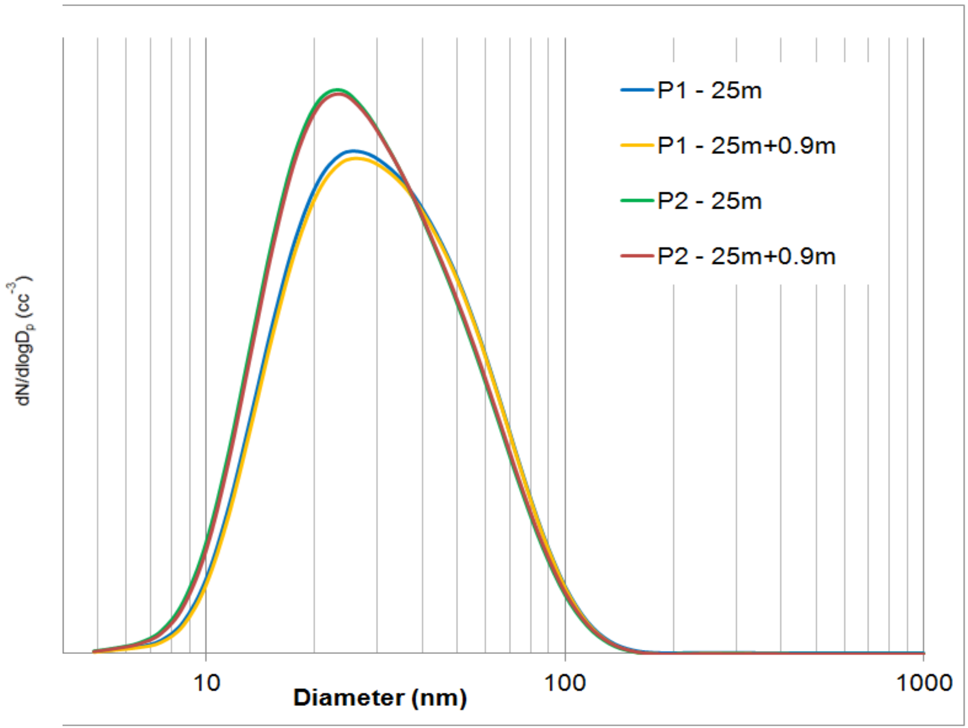

Figure 33 Size distribution graphs for the DMS corrected for initial dilution for large in-production rich burn engine conditions P1 and P2 for sample line lengths of 25 m and 25.9 m for comparison.

7.3.2 Mass instrument comparison

The AVL Micro Soot Sensor and the Artium LII Instrument were compared against each other directly. Both were on similar 5PTS sample line with any theoretical differences in transport line performance being extremely small and can be assumed to be negligible.

As can be seen below in Figure 34, on both engine test campaigns inter-comparison data show good agreement. There appears to be a small bias toward the MSS, however the bias is within 7%, well within the calibration error (estimated to be within 10-16% as per E-31 subcommittee discussion).

The lean burn pilot only test points showed mass concentration values comparable to power conditions of the in-production rich burn engine. Excellent correlation (shown by the R^2 numbers in Figure 34) in the linear regression analysis are presented.

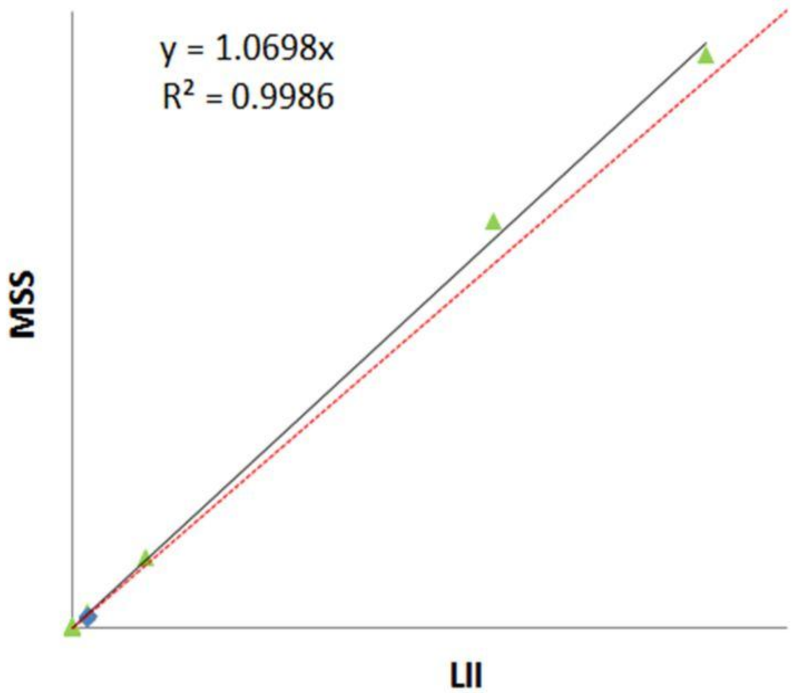

Figure 34 Comparison between different types of AIR6241 mass analysers on EU/EASA system. (Green triangles lean burn pilot only conditions, blue diamonds in-production rich burn engine)

Comparing the two mass instruments by their average mass concentration, as shown below in Figure 35, highlights the variance and the limit of detection of the low mass results that are prevalent in the lean burn staged engine test points.

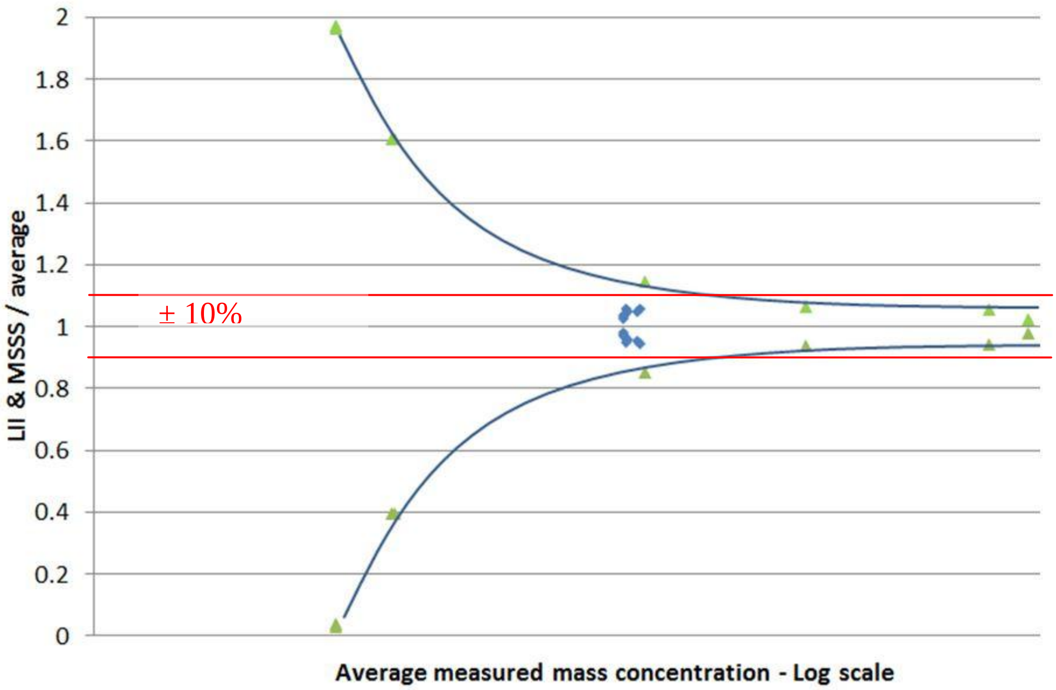

Figure 35 Ratio comparison between different types of AIR6241 mass analysers on EU/EASA system. Note logarithmic scale on x-axis to clearly show the higher variance at concentrations close to instruments LOD. (Green triangles lean staged engine, blue diamonds in-production rich burn engine)

7.4 Limit of detection analysis

For all the measurement instruments (mass, number and size) at the lean staged combustion test conditions, the particle concentrations were either at or below either the instrument's Limit of Detection or engine inlet ambient particle concentration.

We have summarised the discussion below in to: Mass, section 7.4.1; Number, section 7.4.2; and Size, section 7.4.3.

7.4.1 Mass

The Mass results shown below in Figure 36 are an example of a significant signal that is within the optimum dynamic range of the sensors in the mass instrument. There is significant signal disparity between engine exhaust at ICAO levels and a Zero measurement – when only 99.999% pure HEPA filtered Nitrogen diluent is passed through the EU/EASA nvPM system. The sensor signals are of sufficient strength to cover the dynamic sensitivity of the mass instruments that the results trend toward an analogue format.

Conversely Figure 37 shows results at the limit of detection and the discretisation of the data into a semi-digital format. Equivalent engine inlet ambient particle levels are presented to show comparison to the level of readings that mass instruments need to measure at the lowest smoke levels. The LII is showing absolute zero for the Nitrogen diluent sections while the MSS in the settings used was showing a positive offset of about 0.001 mg/m^3. Removing this offset when there is a signal to be measured, would leave very good agreement between the two mass instruments. However at these low mass concentrations, should there be a confidence level for the lean burn staged engine emissions?

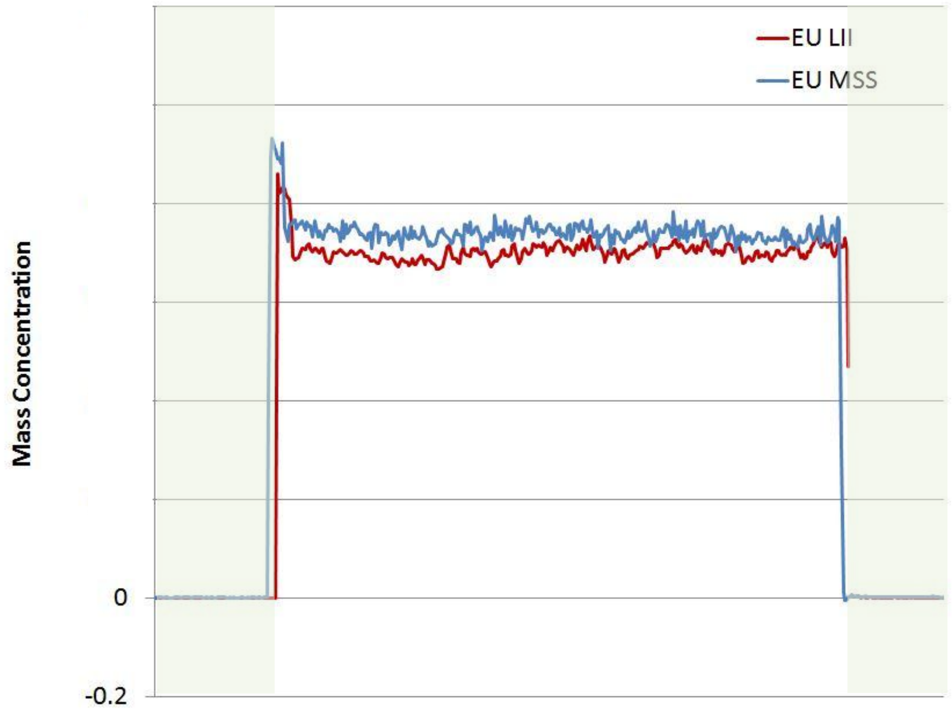

Figure 36 Example of mass instrument signals much greater than LOD (Green shading signifies a Zero measurement – Nitrogen diluent only)

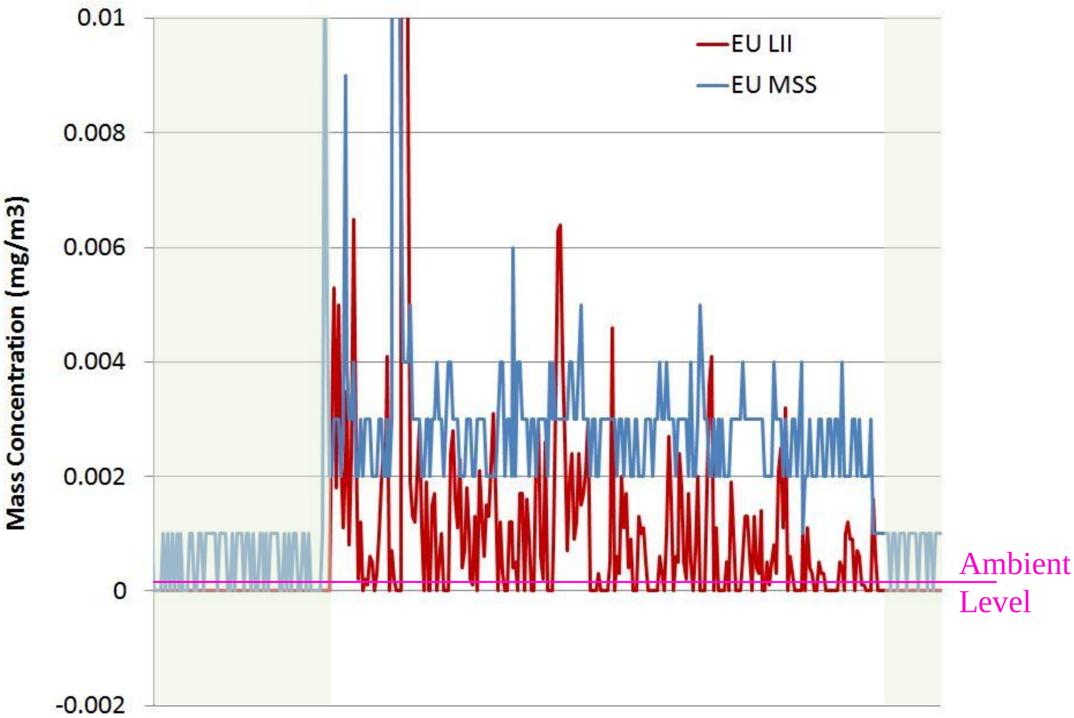

Figure 37 Example of mass instrument signals close to LOD (Green shading signifies a Zero measurement – Nitrogen diluent only)

7.4.2 Number

We can see similar discretisation (as with the mass) with the number instrument signal at the lean staged combustion tests, as can be seen in an example below in Figure 38, where the CPC in the AVL APC is close to its limit of detection. The engine exhaust signal detected shows good agreement with the ambient number level, but close to the zero readings taken.

AIR6241 specifies a leak rate limit of 1 P/cm^3, which as can be seen in Figure 38 the APC meets (the vast majority of the data points during Zero measurement - the shaded sections, are well below 1 P/cm^3). Yet when comparing with equivalent engine inlet ambient particle level the leak rate limit becomes a large factor in the measurement uncertainty. This needs to be assessed when the CPC measurements are at single count figures. The confidence level for measuring a signal (engine or background ambient) close to the ambient number concentration needs evaluating.

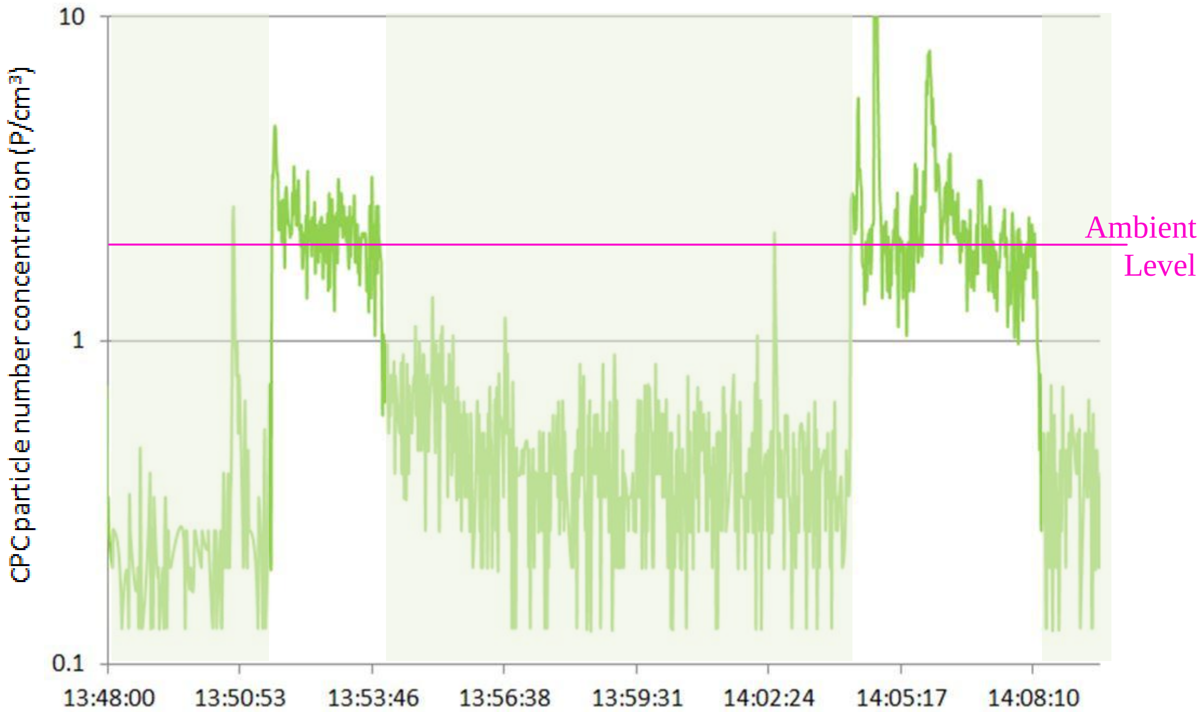

Figure 38 Example of CPC raw signal close to LOD (Green shading signifies a Zero measurement – Nitrogen diluent only)

These results (both mass and number) where the signal becomes discrete are a known behaviour that is studied more in depth in telecommunications with the limits of signal detection and is widely documented in scalar data sensors.

7.4.3 Size distribution

The observed discretisation in mass and number instruments is not reproduced in the sizing instruments as they are vector instruments measuring two variables.

For the size instruments, test engine conditions T5 to T8 – representing lean staged combustion – were at the limit of detection. The DMS ran without any internal dilution in T6, T7 and T8 but with an internal rotary disc dilution of 20:1 at T5. The size distribution graph –

not corrected for any internal or external dilution so as to highlight the limits of detection of the DMS500 – is shown with Zero and ambient readings for comparison below in Figure 39.

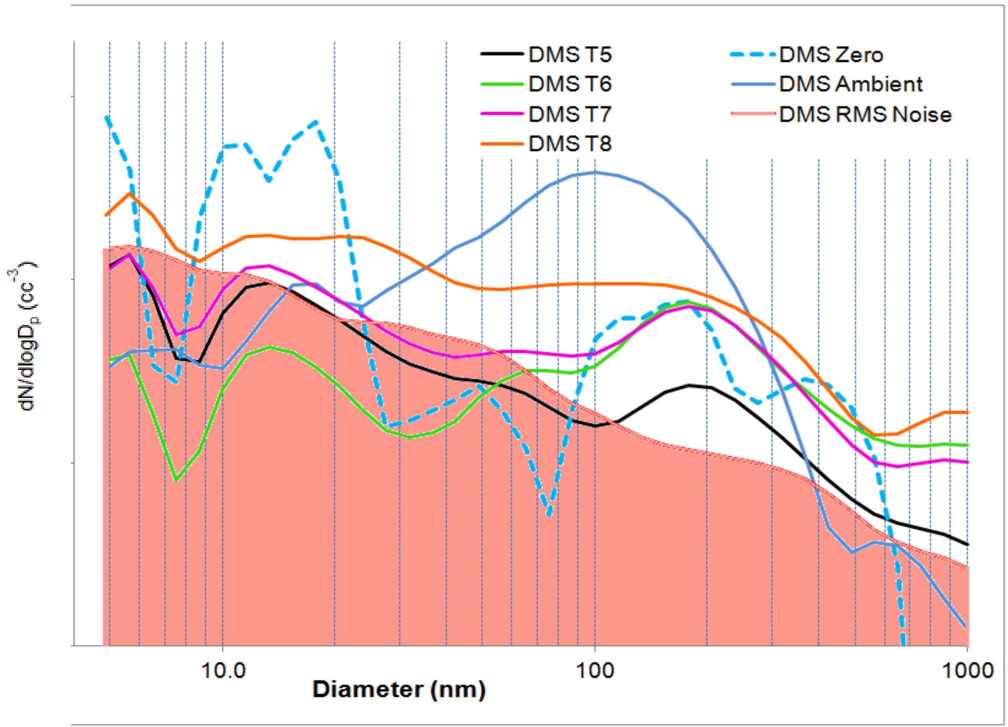

Figure 39 DMS500 Size Spectral density chart showing the zero, ambient and RMS limits of detection against the lean burn engine conditions at T5, T6, T7 and T8.

Take note of the shaded area under the RMS noise line – within this area any signal was indistinguishable from background noise. We can see for T5, T6 and T7 that below the signals were too small for the DMS. T8 is significant as is ambient level measurement. The zero reading that records a significant presence in or around 10 to 20 nm and 100 to 500 nm is anomalous as there should be no particles in the diluent – a possible explanation however is this reading was obtained 3 hours before the test and the DMS was still within its warm-up period.

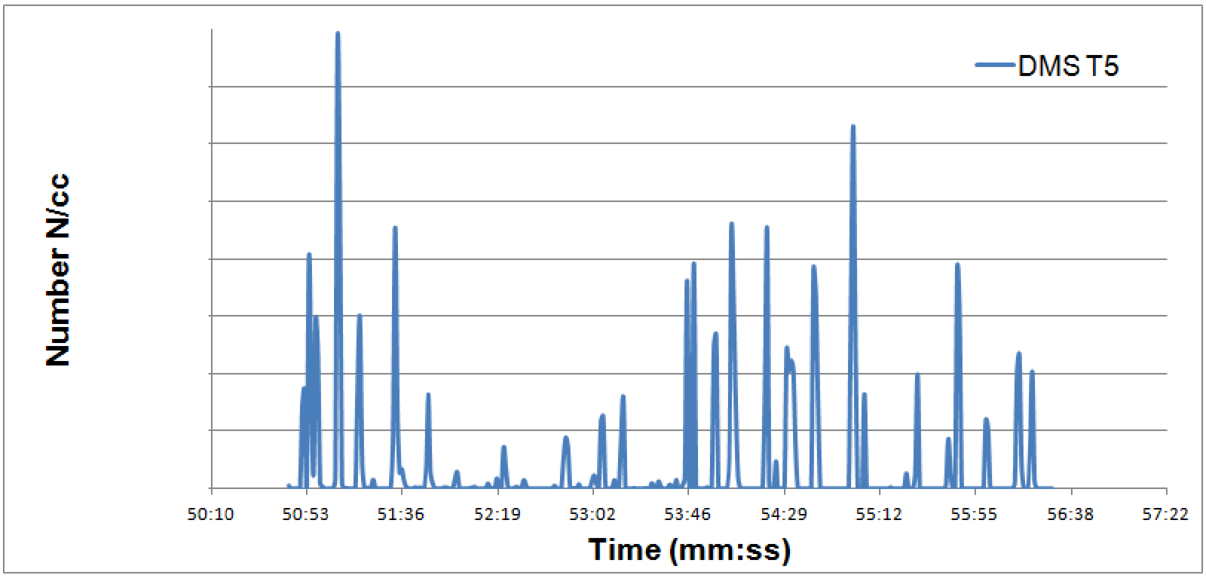

Figure 40 DMS500 Total particle number for the T5 lean burn staged condition, showing the spikes in recorded PM.

All of the lean burn staged condition test cases showed irregular behaviour in the electrometers. Figure 40 shows the T5 condition, with the DMS recording spikes of signals of significant strength at frequent but not regular intervals. As these spikes are not observed in the mass or number analyser signals, this could be explained by particle shedding, from the 5PTSaux sample line or DMS internal disc diluter, whether the particle morphology is unchanged is unknown.

Given the low concentration levels shown in the size instruments, mirroring what is shown in the mass and number instruments (discussed in sections 7.4.1 and 7.4.2), should there be more effort being given to qualify low levels of detection or should greater consideration be given to measurements having a large level of uncertainty? In either case comparisons are needed with other instruments for lean burn conditions, such as an Optical Particle Counter (OPC), for recording more accurately the low number levels of large (>250 nm) PM.

7.5 Line loss correction analysis

7.5.1 Introduction

Local air quality and climate impact nvPM modelling requires accurate estimation of engine exit plane nvPM values. The aim of the Line Loss Correction Analysis (LLCA) is to use the measured number and mass concentrations at the respective ends of the sampling system and estimate the number and mass concentrations at the exit plane of the engine. The ratios of the concentrations at the exit plane : sample system end yields facn and facm, which are the factors by which the number concentration (facn) and mass concentration (facm) are reduced by losses down the respective sampling system. The challenge with estimating facn and facm is that losses are size dependent; however, the proposed nvPM calculation methodology (based on draft nvPM ARP in turn based on AIR6241) does not support size distribution measurements (due to traceability, data inversion robustness and instrument time response issues), therefore it is necessary to model the size distribution at the end of the sample line based on the measured parameters and a series of assumptions. Details of which are presented below in Section 7.5.2. This in turn allows the distributions at the engine exit plane (and hence the engine exit plane total mass and number) to be determined, provided the size dependent losses are known.

In addition to the measured total number and mass during SC03 and SC05, size distribution measurements were taken using a DMS and SMPS, as detailed in section 7.3. The SMPS measurements were used to validate the modelled size distributions generated from the LLCA. The measured distributions were also used in the LLCA to calculate the facn and facm based on measured data to compare with the modelled data. The methodology, analysis and the conclusions from these measurements are presented in the following sections. Finally, the effects of varying the parameters assumed to be constant in the LLCA methodology are reported.

7.5.2 Methodology

The methodology for the LLCA has been presented at several meetings, including the 16th ETH Conference on Combustion Generated Nanoparticles[a] and the SAE E31 sub-committee annual meeting 2014 in Boston[b]. The details of the methodology are also described in an SAE draft document (proposed as AIR6504). An outline of the LLCA is shown in the flow chart in Figure 41 which is a representation of the Excel spreadsheet generated by the E31 line loss team, used to calculate facn, facm, $N_{exitplane}$ (the total number at the exit plane) and DGN.

The approach is to model the exit plane size distribution as a log-normal, which is defined as:

$$\frac{dn}{d\ln(d_p)} = \frac{N_{exitplane}}{\sqrt{2\pi}\ln(\sigma_g)}.e^{-\frac{1}{2}\left(\frac{\ln(d_p)-\ln(DGN)}{\ln(\sigma_g)}\right)^2}$$

Equation 1

Where d_p is the diameter, DGN is the geometric mean diameter by number, $N_{exitplane}$ is the exit plane number concentration and σ_g is the width of the distribution, which is assumed to be 1.8. In the model, DGN and $N_{exitplane}$ are variables. By assuming a density of 1 g/cm^3, this number distribution is converted to a mass distribution. The size dependent losses are then applied to these distributions to generate a modelled size and mass distribution at the end of each segment of the sampling system, which are summed to give a total number and mass concentrations, which are then compared to the measured values. The approach can be broken down into 5 steps (highlighted by the numbers in red in the flow chart):

1. The measured number and mass concentrations are inputted and the spreadsheet solver function is run. This starts a loop which minimises the square of the fractions errors, namely:

[a] Hagen et al., 2012.'Correlation between mean size and number and mass concentrations for jet engine soot'. 16th ETH Conference on Combustion Generated Particles.

[b] Williams; Hagen. Presentations at the SAE E-31 annual committee meeting, Boston, 2014.

$$\chi^2 = \left(\left(N_{measured} - N_{exitplane}\right) / N_{measured}\right)^2$$

2. The DGN and exit plane total number are varied to produce a new log-normal distribution, given by Equation 1, and using an assumed sigma of 1.8.
3. The new number and mass distributions are defined, using an assumed density of 1 g/cm^3 for the mass, and by summing the distribution, the exit plane number and mass concentrations are calculated. The exit plane total number in this step should be the same as in step 2.
4. The size dependent loss corrections are applied to the modelled engine exit plane distributions using the UTRC line loss model for the number and mass, and the VPR loss and CPC efficiency for the number distribution are added.
5. These distributions are summed to give the modelled total number and mass concentrations at the end of the sampling system. They are compared with the exit plane concentrations to yield facn and facm; they are also compared with the measured values by calculating the square of the fractional error.

The loop 2 to 5 repeats until the program has found the minimum value of the square of the fractional errors and outputs facn, facm, DGN and $N_{exitplane}$.

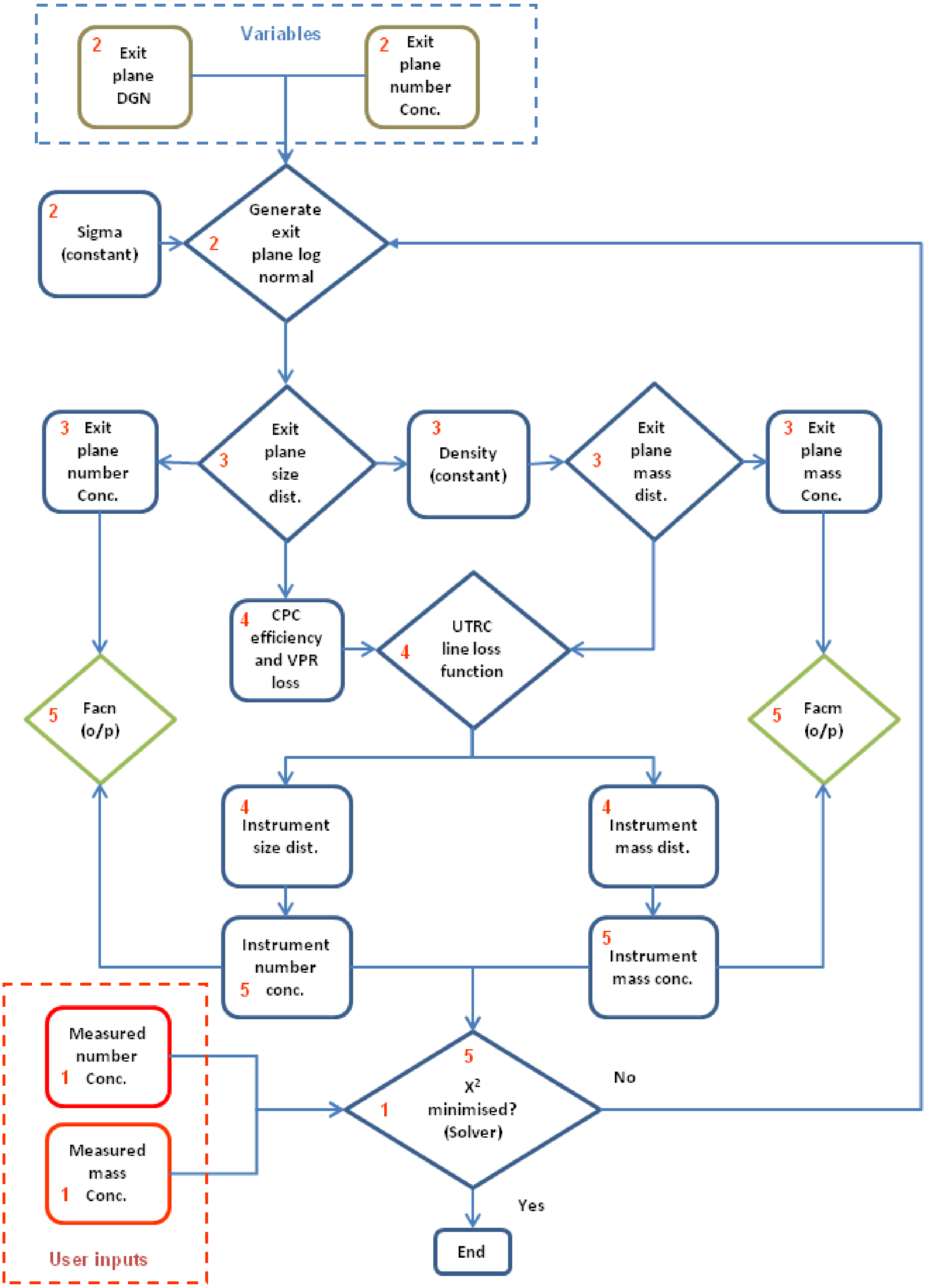

Figure 41 Line Loss Correction Analysis (LLCA) Flow Chart

7.5.3 Line loss correction for Lean burn staged engine

The lean burn staged engine is a development engine, therefore only relative particle concentrations are shown for proprietary reasons. The values of facn and facm are heavily dependent on the losses within a given sampling system, therefore the particle transport losses for this specific test campaign, used in the correction calculations, are presented in detail below.

7.5.3.1 *Sampling system (UTRC model)*

The UTRC model, which accounts for particle transport losses due to diffusion, thermophoresis, inertia, electrostatic forces and curvature, was shown to perform well experimentally in SAMPLE III SC03. The model accounts for particle transport losses from the sampling tip (1PTS) to the end of the 5PTS line, but excludes the VPR loss and CPC efficiency. The total UTRC system losses using this model for the EU/EASA systems for test points T1 – T6 are shown in Figure 42 below. Test points T7 and T8 had the same thermophoretic loss as T6 so are excluded for clarity. It shows the effect of probe entry temperature on the overall loss, but for each test point the overall trend is the same.

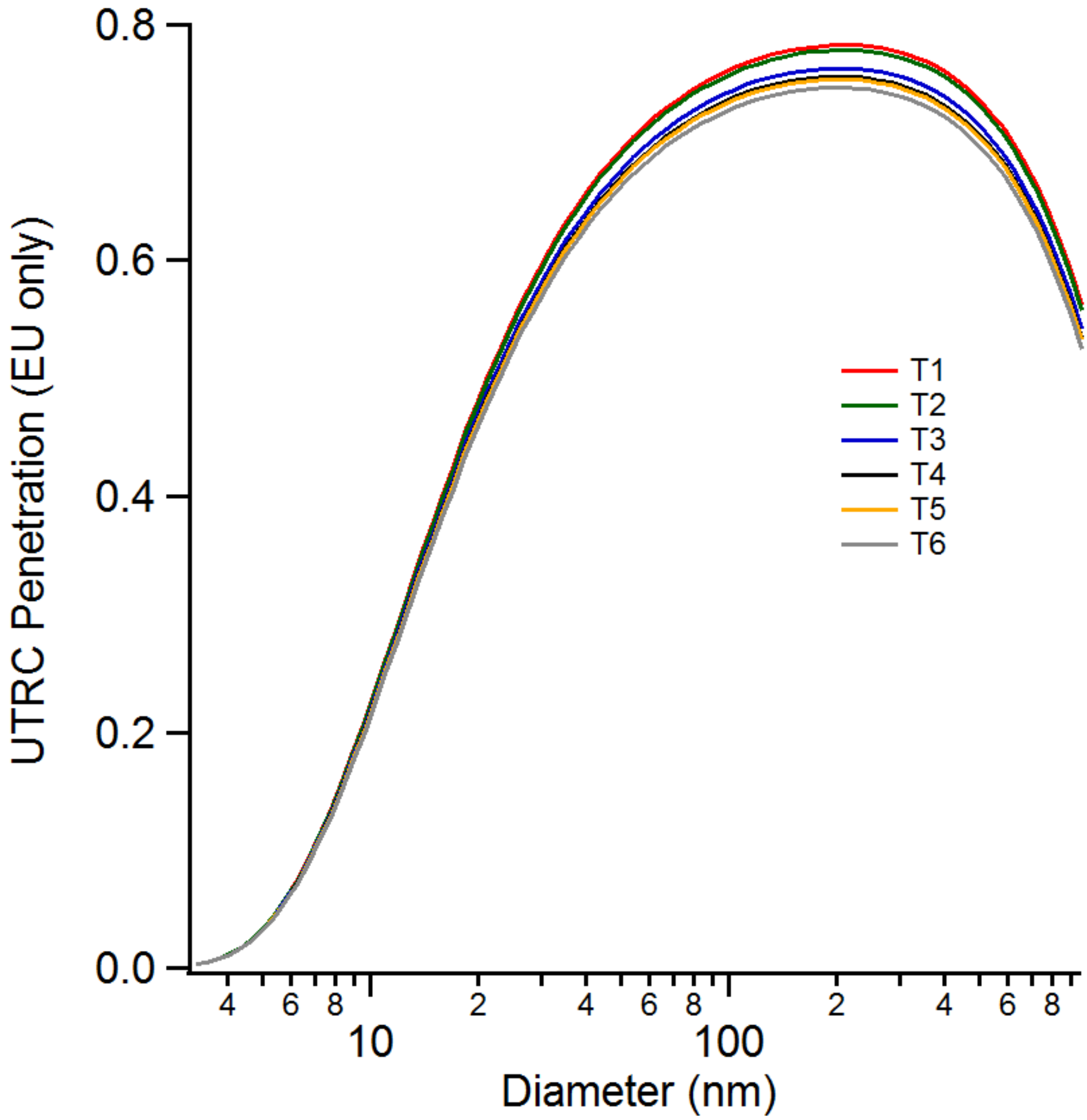

Figure 42 EU/EASA UTRC modelled line loss

Figure 43 below shows a comparison of the EU/EASA and RR system for test points T1 and T6, which represent the extremes of the probe entry temperatures experienced. This shows that the modelled losses in the two systems from 1 PTS to 5PTS are very similar in both trends and magnitudes.

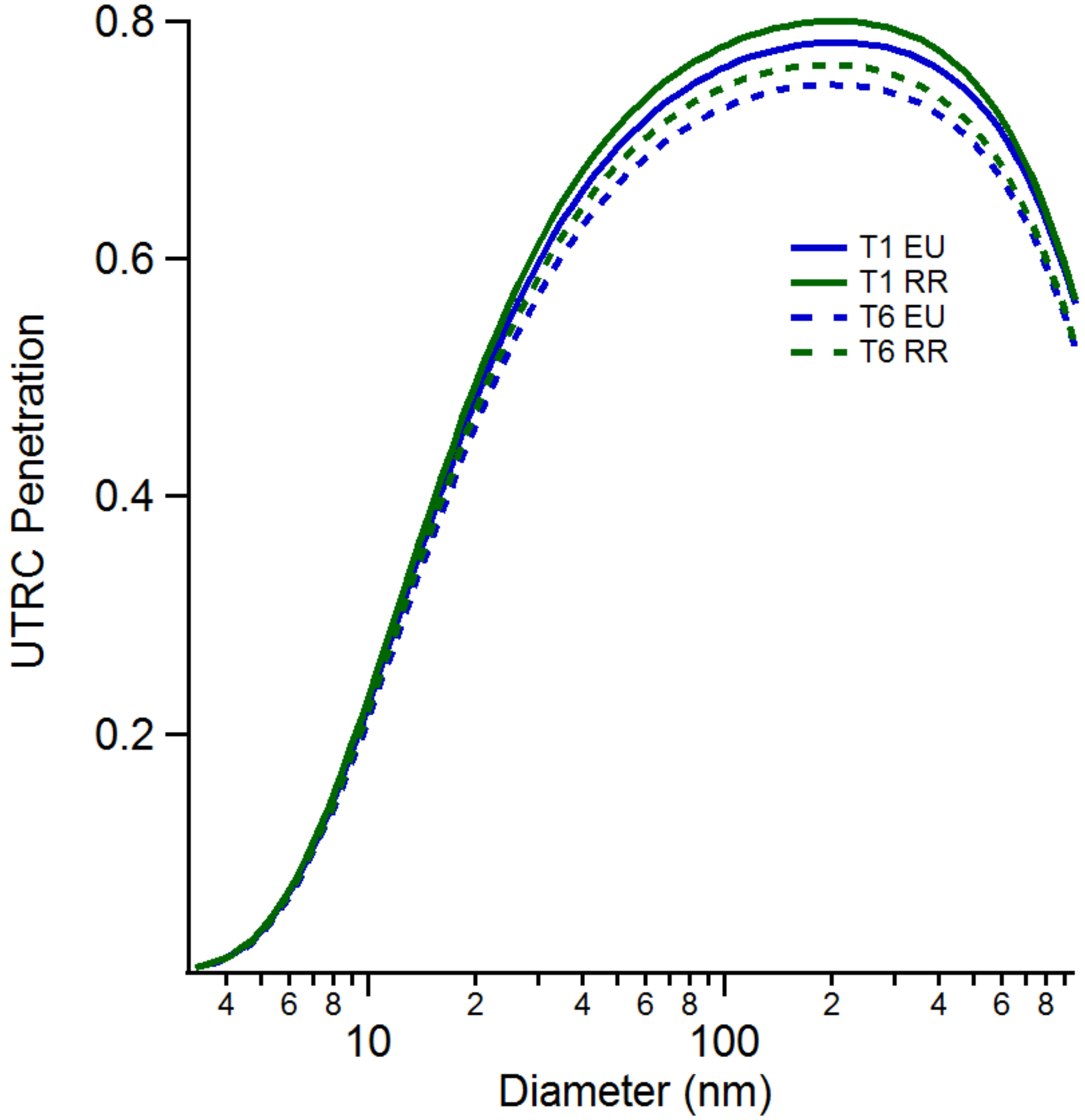

Figure 43 EU/EASA Comparison of the EU/EASA and RR system losses based on the UTRC model.

Within each system, there are slight system geometry differences , for example in the 5 PTS oven where the line splits to the number and mass instruments. The pipes have different lengths and flows. The losses of the sampling system to the number and mass instruments, labelled 5PTSn and 5PTSm respectively, are shown in Figure 44 below for the RR system at test point T1. This clearly shows that these small differences have a negligible effect on the overall loss. The largest contributions to the losses are the tip temperatures and losses down the 25 m 4PTS lines.

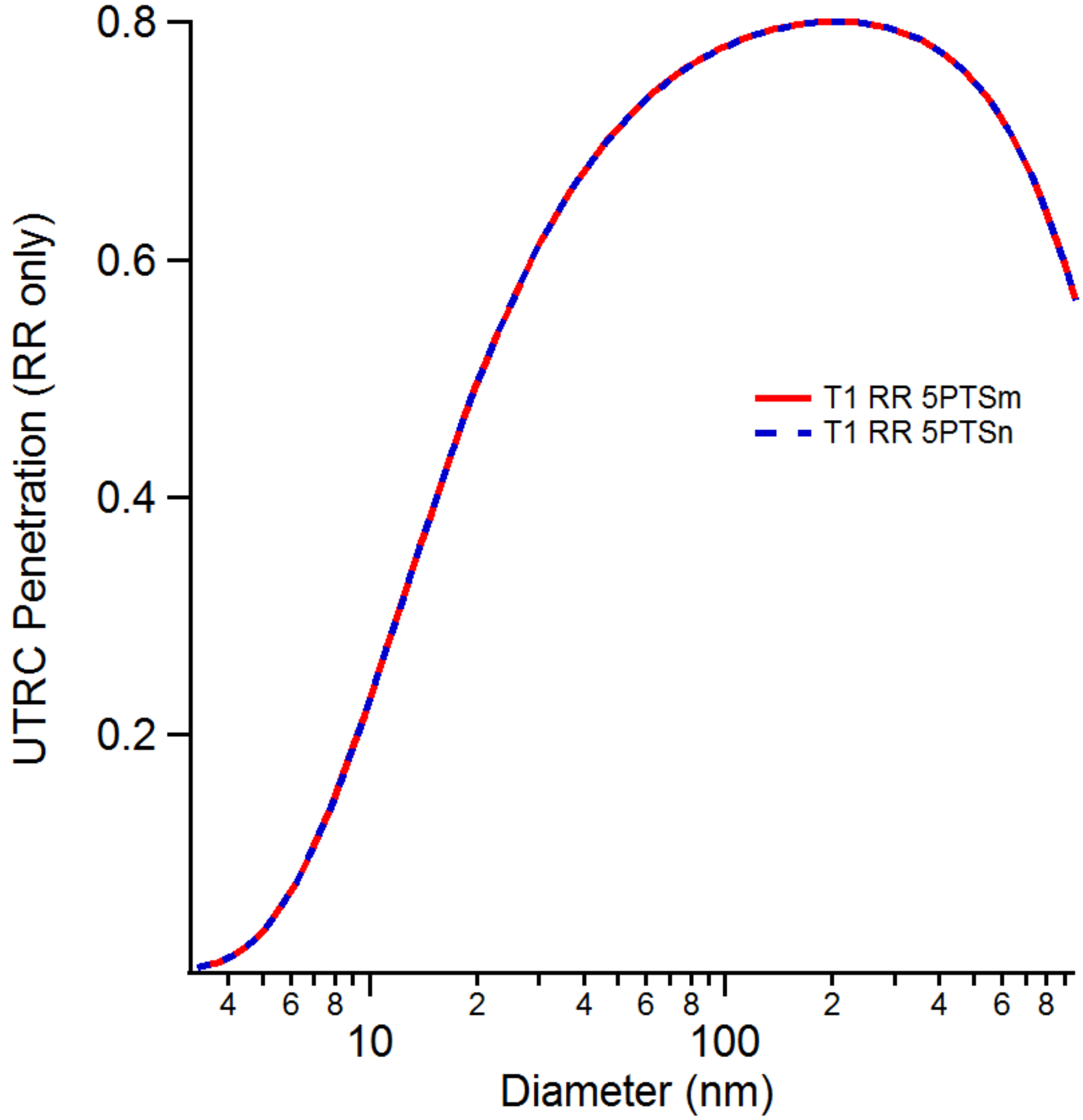

Figure 44 Comparison of line losses to the mass and number instruments.

7.5.3.2 *VPR*

In addition to the UTRC system loss, the number measurement system has two additional losses. One of those is the VPR. The losses in the VPR are based on a combination of AIR6241 compliant measured data supplied by the manufacturer and the theoretical thermophoretic and diffusional losses as predicted by the line loss correction SAE E31 (AIR6504) drafting team spreadsheet. Figure 45 below shows the measured and modelled data for the EU/EASA and RR VPRs. The modelled data is based on the approach outlined in the AIR6504 draft. Assuming at 100 nm diffusional losses are negligible and therefore the measured loss represents the thermophoretic loss, the calculation uses a dimensionless parameter called μ, which is defined as μ = D.L/Q, where D is the diffusion coefficient, L is the length of the system and Q is the flow through the system. A non-linear curve fitting routine using the Levenberg-Marquardt algorithm was used to find the best-fit of the model by allowing L and Q to vary. Using the line loss team approach of modelling the losses through the VPR as a simple combination of thermophoretic and diffusional losses works well for the RR system, and this model has been used in the calculation of RR system losses. For the EU/EASA system, the line loss team model is less good. Therefore an improved model was fitted based on the actual measured data for Dp ≥15 nm and the line loss team model for Dp < 5 nm. This is defined as:

$$fit = y_0 + \frac{A}{((x - x_0)^2 + B)}$$

Where A and B are constants. It is not suggested that this is a physically meaningful description of the data, purely a mathematical fit to the data. This fit is used in the following line loss calculations for the EU/EASA system. However, all data below 15 nm is an extrapolation to measured data which carries with it an uncertainty. It is also worth noting the difference between the two systems, with the RR system having less loss. This difference in particle penetration between VPR manufacturers is consistent with VPR penetration data obtained during SAMPLE III SC01.

The impact of these above factors will be demonstrated in the later sections.

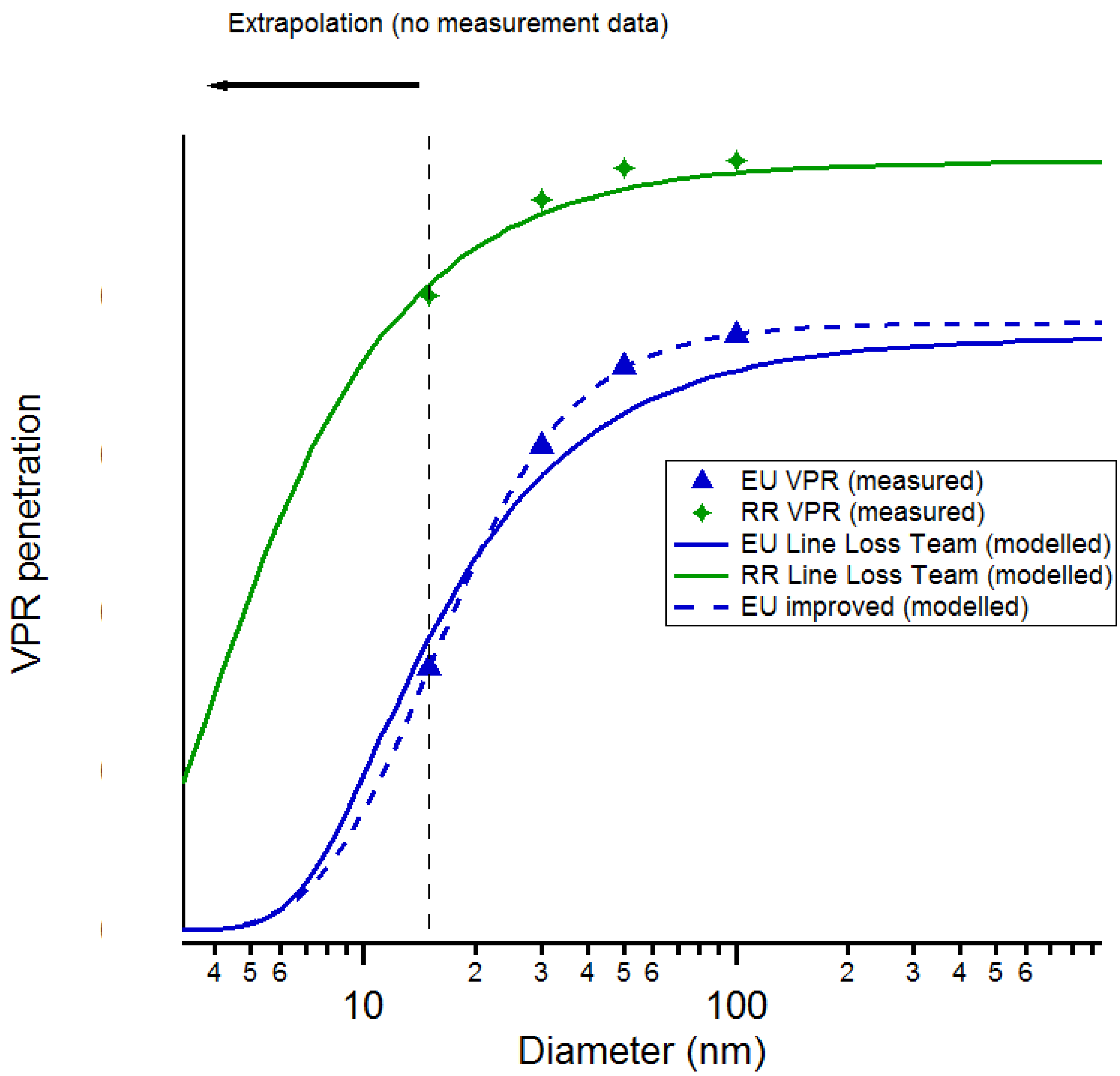

Figure 45 EU/EASA and RR modelled and measured VPR penetration efficiencies.

7.5.3.3 *CPC efficiency*

The CPC efficiency is modelled assuming a D_{50} of 10nm and a D_{90} of 15nm. This is shown in Figure 46 below.

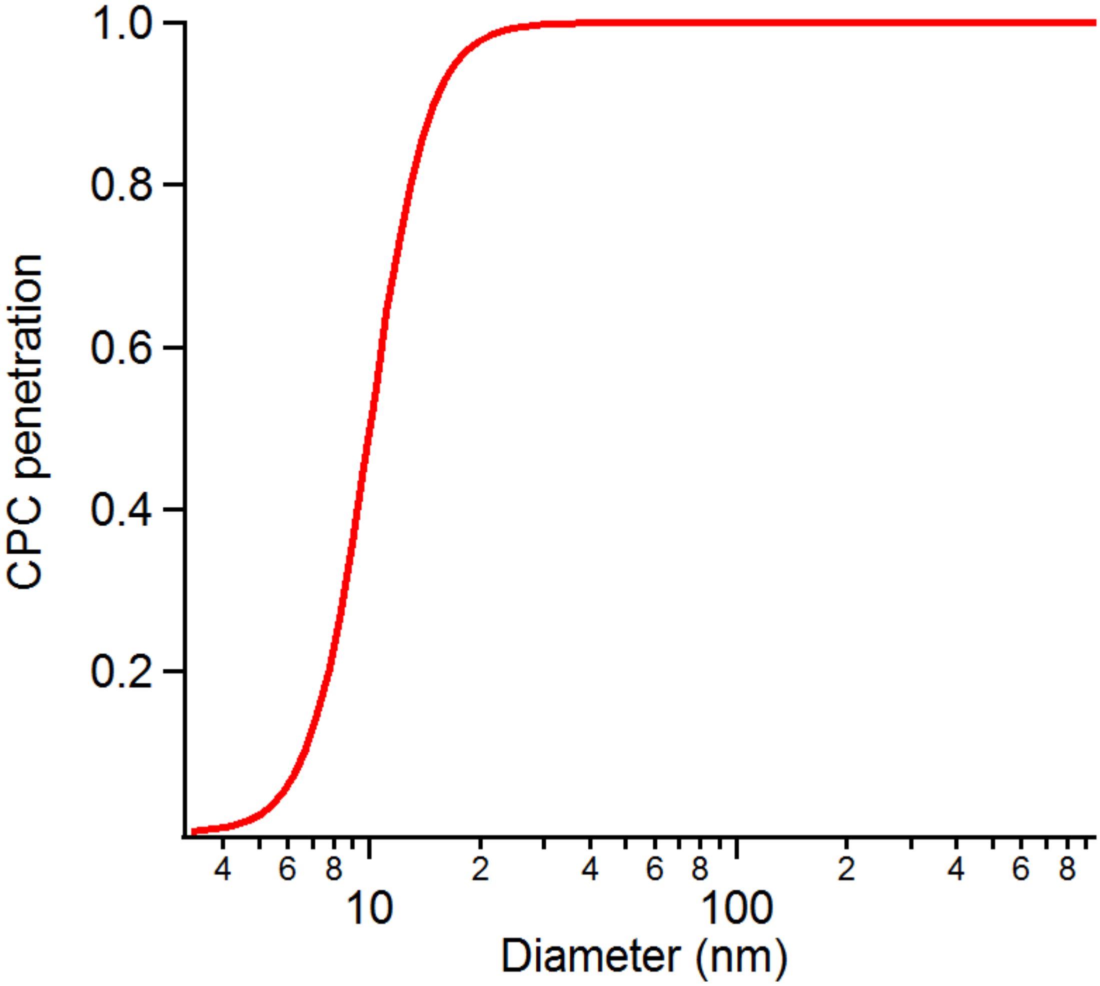

Figure 46 CPC efficiency.

The combined penetration of all three losses is shown below in Figure 47 for T1 and T6 for both systems. The influence of the different VPR losses can be seen at all sizes, and as will be shown later, the effect at small sizes is quite profound. This effects the calculation of facn and facm.

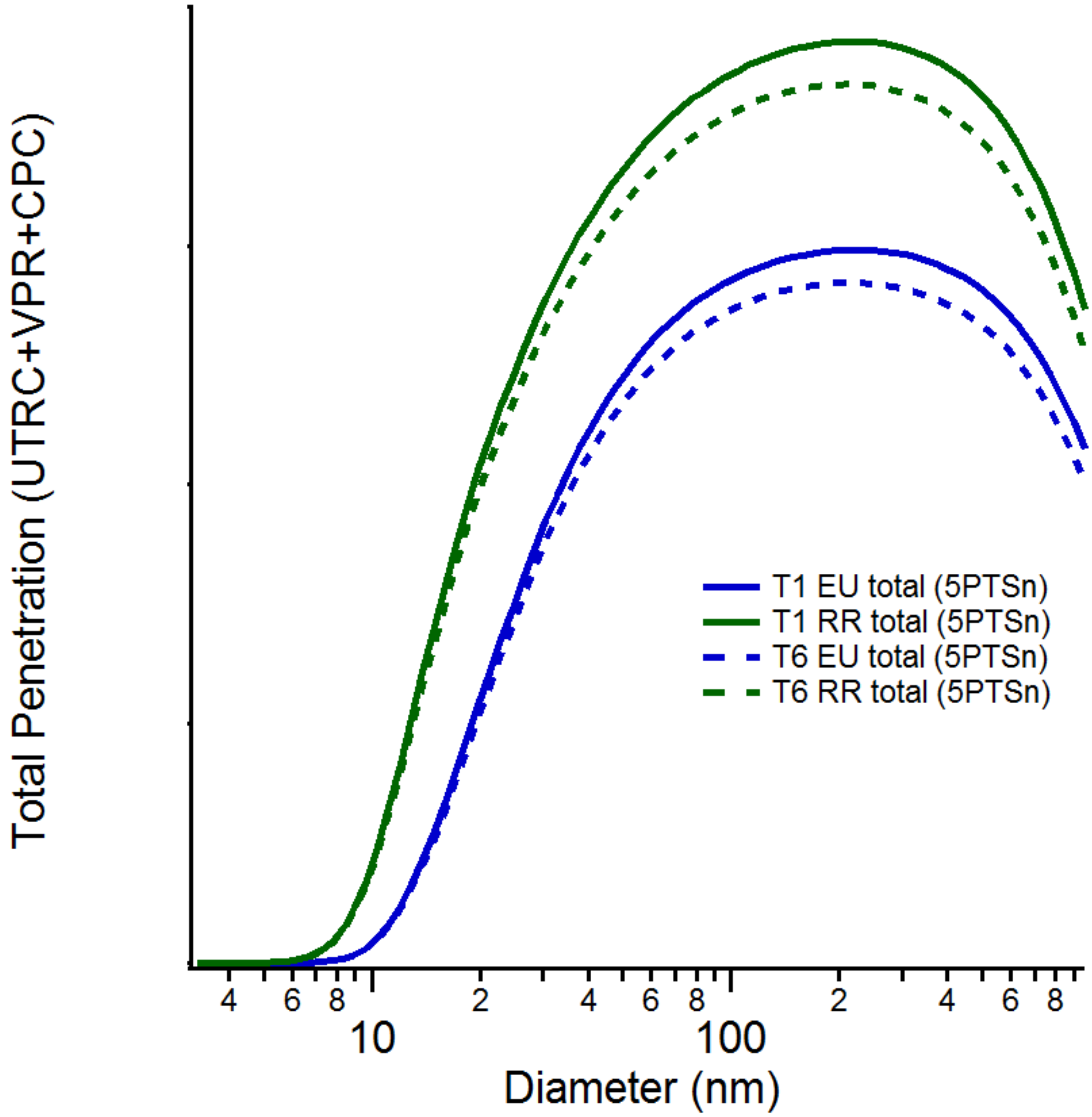

Figure 47 Total number line losses for T1 and T6 for the EU/EASA and RR systems.

7.5.3.4 *Lean burn staged engine results – facn, facm and DGN*

The results from the RR and EU/EASA reference system using the model outlined in Section 7.5.2 and the measured number and mass concentrations are shown below in Table 8. The table has facn and facm for Dp > 10 nm and Dp > 3.28 nm, the lower limit of the model.

The results show some significant differences between the facn for the two systems, with the EU/EASA system always reporting a larger facn. The facm values are similar and do not vary much with the lower size cut.

Table 8 Results of the modelled LLCA using the measured total number and mass. Numbers in red are unreliable results.

	EU /EASA	RR	EU /EASA	RR	EU /EASA	RR	EU /EASA	RR	EU /EASA	RR
Test point	DGN		Dp > 10nm				Dp > 3.28nm			
			facn		facm		facn		facm	
T1	13.1	13.5	5.46	2.78	1.61	1.56	7.99	3.97	1.63	1.58
T2	16.9	20.3	4.47	2.29	1.53	1.43	5.48	2.59	1.53	1.43
T3	25.9	30.7	3.26	1.93	1.43	1.37	3.44	1.98	1.43	1.37
T4	30.1	36.6	2.96	1.81	1.41	1.36	3.06	1.83	1.42	1.36
T5	60	60	2.12	1.56	1.36	1.33	2.13	1.56	1.36	1.33
T6	60	60	2.14	1.58	1.37	1.34	2.14	1.58	1.37	1.34
T7	46.8	60	2.36	1.58	1.38	1.34	2.37	1.8	1.38	1.34
T8	40.3	60	2.53	2.87	1.39	1.34	2.55	1.58	1.39	1.34

The differences between the systems are explained by the line loss functions. A larger correction is applied to the EU/EASA system at smaller sizes (see section 7.5.3.1), so the calculated total number at the exit plane is larger. This is shown in Figure 48 below for T1 and T4

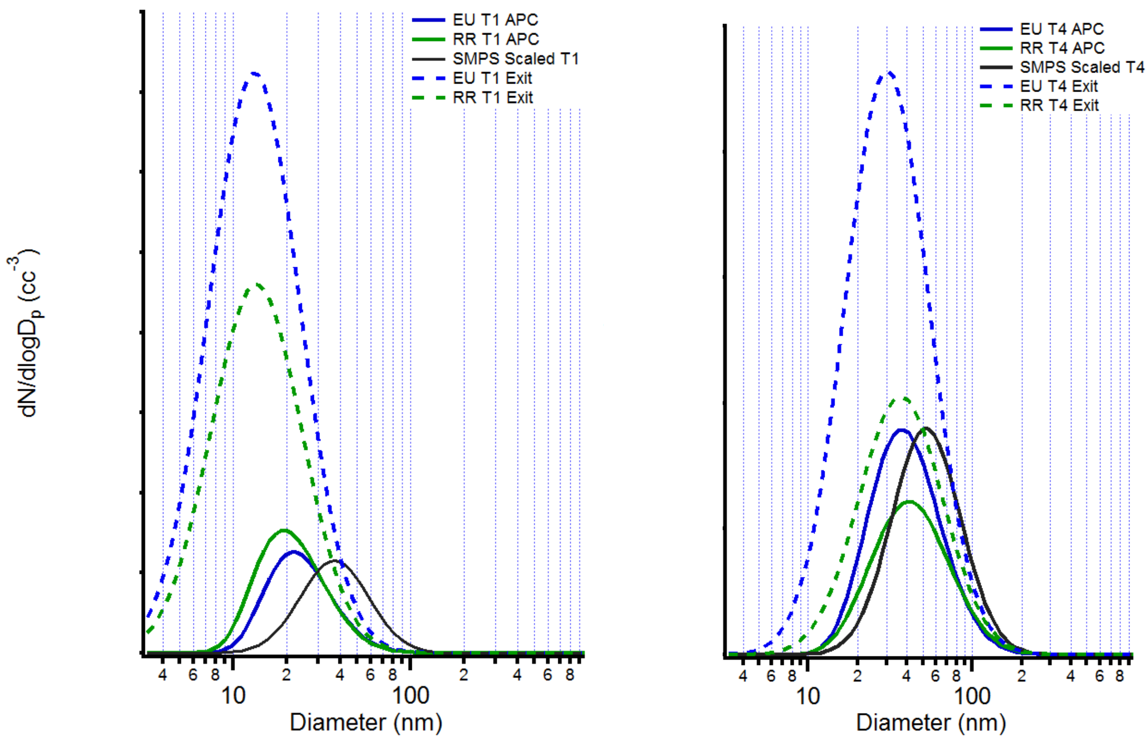

Figure 48 T1 and T4 exit plane and APC size distribution from the modelled data and the measured size distributions at the APC exhaust.

Figure 48 shows that the relatively small differences in the modelled size distributions at the APC are producing large differences in the predicted engine exit plane distributions. A summary of the differences is shown in Table 9 below. Whilst the absolute values of the measured number and mass at the APC and LII are not given, the relative fractions, that being

((RR – EU)/RR) are provided in Table 8. The values used are corrected for DF1 for both number and mass and for PCRF for number.

Table 9 Differences between the RR and EU/EASA systems for Dp > 10nm.

Test point	APC number	LII Mass	DGN	Exit plane number	Exit plane mass	facn	facm
T1	21.8%	-39.9%	2.96%	-53.7%	-44.6%	-96.4%	-3.21%
T2	-12.7%	-28.9%	16.8%	-119.8%	-37.4%	-95.2%	-6.99%
T3	-8.5%	-8.3%	15.6%	-82.7%	-13.4%	-68.9%	-4.38%
T4	-35.9%	-20.7%	17.8%	-122.6%	-26.0%	-63.5%	-3.68%

The results show that the modelled DGN is larger in the RR system, which is another consequence of the line loss functions. The variation in the corrected number and mass values is significant and frequently larger than the E31 estimated ±25 % variability in uncorrected system data. Furthermore, the table shows that the differences in the engine exit plane predicted number and mass are larger than the differences between the corrected APC number and LII mass, especially for the number. This is again an effect of the line loss correction differences and highlights the importance of having reliable line loss functions. Both results cannot be correct as the instruments were measuring the same sample and therefore the engine exit plane concentrations should be the same, within instrument measurement uncertainties.

Table 8 has several data points highlighted in red. These are data points that the solver in the line loss team spreadsheet did not find a good solution. The solver has two limits. Firstly, the exit plane total number must be greater than 0. Secondly, the range of DGN permitted is 5 nm ≤ DGN ≤ 60 nm. The points highlighted in red were limited to a DGN of 60 nm. This meant that the modelled APC and LII number and mass concentrations did not match the measured values. This is a limitation of the current approach where a density of 1 g/cm^3 is used.

It is important to understand how the values of DGN, facn and facm vary within the model. To investigate this, the values for T4 from the EU/EASA system were varied by +/- 20 % (for number and mass). This allows an indication of the sensitivity of the model to changing conditions. The results of this are presented below in the colour contour plot, Figure 49.

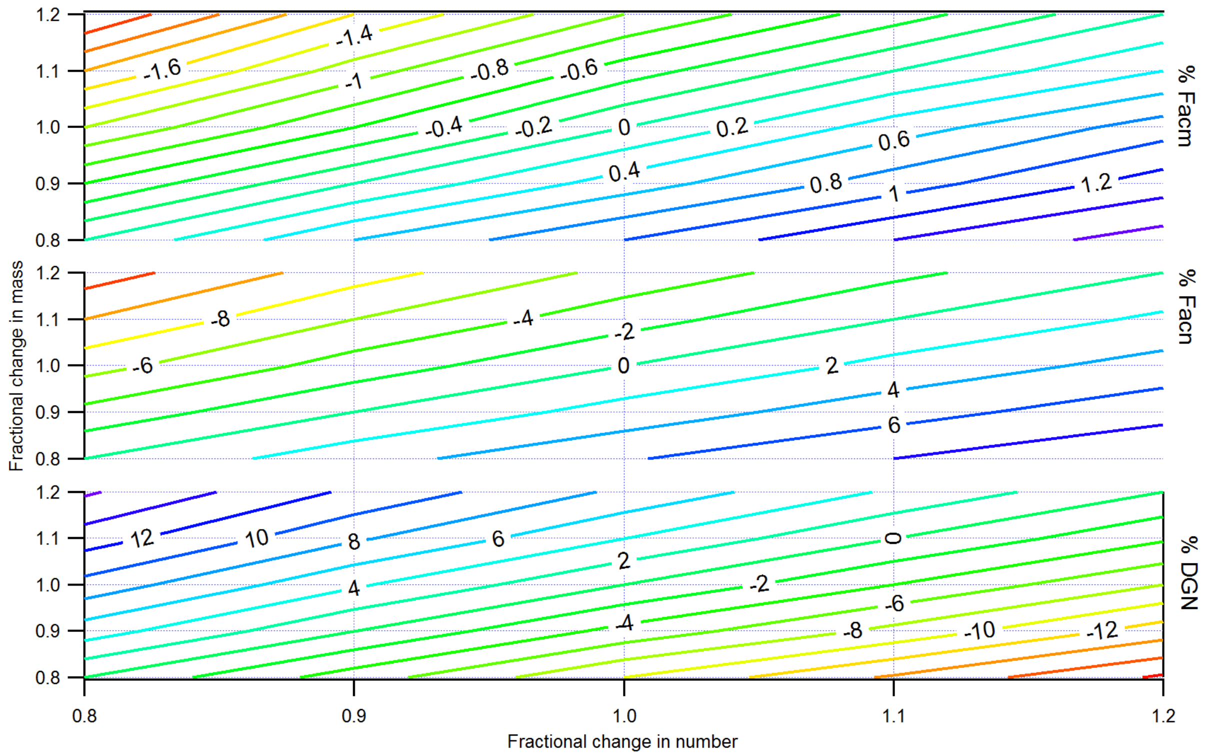

Figure 49 Contour plot of percentage changes in DGN, facn and facm for varying inputs at T4.

The graphs shows that DGN is the most sensitive parameter to changes in the number and mass, varying by up to ~18 %, followed by the facn with a maximum variation of ~13 % and finally facm, which shows little sensitivity to changes in input conditions, varying by up to ~2.5 %. However, for T4, the engine exit plane DGN and the modelled instrument diameters both lie on the penetration curve where small changes in diameter result in small changes in penetration. For T1, the DGN falls on the curve where small changes in diameter leads to large changes in penetration. Therefore, results from using modified data from T1 and T4, where the number has been increased by a factor of 1.2 and the mass reduced by a factor of 0.8, are shown below in Table 10.

Table 10 Changes in EU/EASA modelled parameters as a function of DGN

	EU original	EU modified	Differences		
Test point	DGN (nm)		DGN (%)	facn	facm
T1	13.1	9.97	23.9%	-24.9%	-8.7%
T4	30.1	25.2	16.3%	-13.1%	-2.4%

Once again, the effect of particle size and hence penetration can be seen. When changes in penetration with size are small (i.e. at largest particle sizes), the effects of changing the input values are smaller than when changes in the penetration with size are large (i.e. at the smallest sizes). Though instructive, this work highlights the need to perform a full error analysis on the model, taking account of all uncertainties in the predicted line loss and measured data.

7.5.3.5 *Lean burn staged engine - measured vs modelled data*

Section 7.5.3.4 above used the measured APC and LII values as inputs to the LLCA. In addition, SMPS measurements were also obtained for T1 – T4. These results are shown in Figure 32 in section 7.3.1. In summary, the SMPS was connected to the exhaust of the APC. Log-normal distributions were fitted to the raw distributions, and the distributions were corrected for DF1 and the penetration loss. In addition, corrections were made to account for the transport down the ~1m line connecting the SMPS to the APC exhaust. Finally, the ratio of the SMPS total number : APC total number (averaged over the same scanning periods as the SMPS) was used to scale the SMPS distributions to account for STP and correct for any under counting in the SMPS (due to charging efficiency). The final scaled distributions are shown below in Figure 50. As previously discussed, for T5 – T8, the concentrations recorded were below the limited of detection of the SMPS. The raw distributions presented in section 7.2 showed little evidence of particles below ~10 nm, which is consistent with observations from other SAMPLEIII SC02 and SC03 measurement campaigns. However, the mathematical fits do produce a non-zero tail at Dp < 10 nm. This potentially affects the data, as will be shown later.

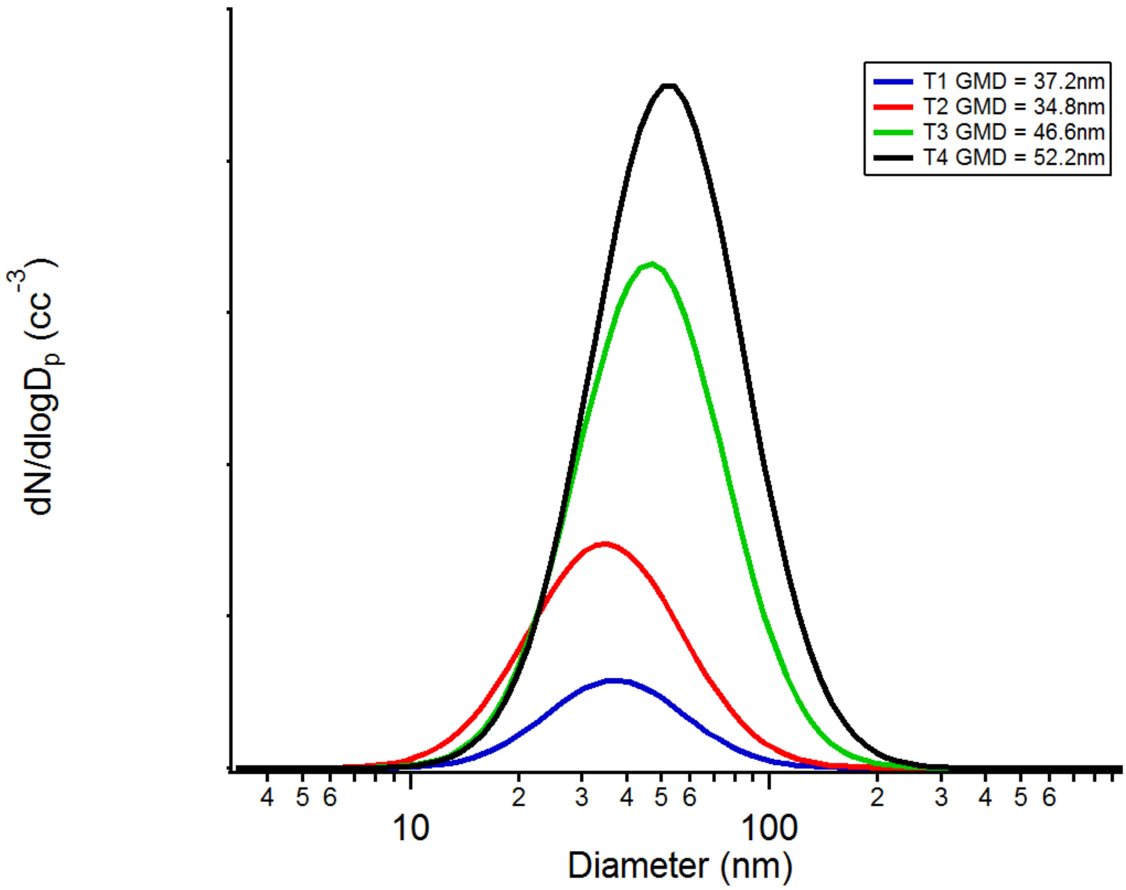

Figure 50 Final scaled, log-normal distributions derived from SMPS data.

These measured values can be compared with the modelled distributions to investigate the effectiveness of the model. Figure 48 in section 7.5.3.4 showed the SMPS distributions with the modelled results. It can be seen that the modelled modal diameter at the instruments is smaller than the measured diameter reported by the SMPS. In Section 7.3.1, the SMPS was compared with a DMS run simultaneously. The results showed that the SMPS and DMS agreed well, with the DMS reporting a slightly higher DGN. The predicted mean diameter from T2 and T3 were also smaller than the measured diameter. The SMPS was calibrated with traceable polystyrene latex spheres and the CPC was within the annual TSI calibration. It appears that the approach used to model the particle properties is under predicting the modal diameter using the assumptions stated.

The UTRC line loss model and the VPR loss model can be applied to the SMPS distributions to predict the engine exit plane size distributions. This is the opposite of the procedure described above where the predicted engine exit plane distribution is scaled by the line losses to predict the instrument distributions. The results of this are shown in Figure 51 below, along with the EU/EASA exit plane results.

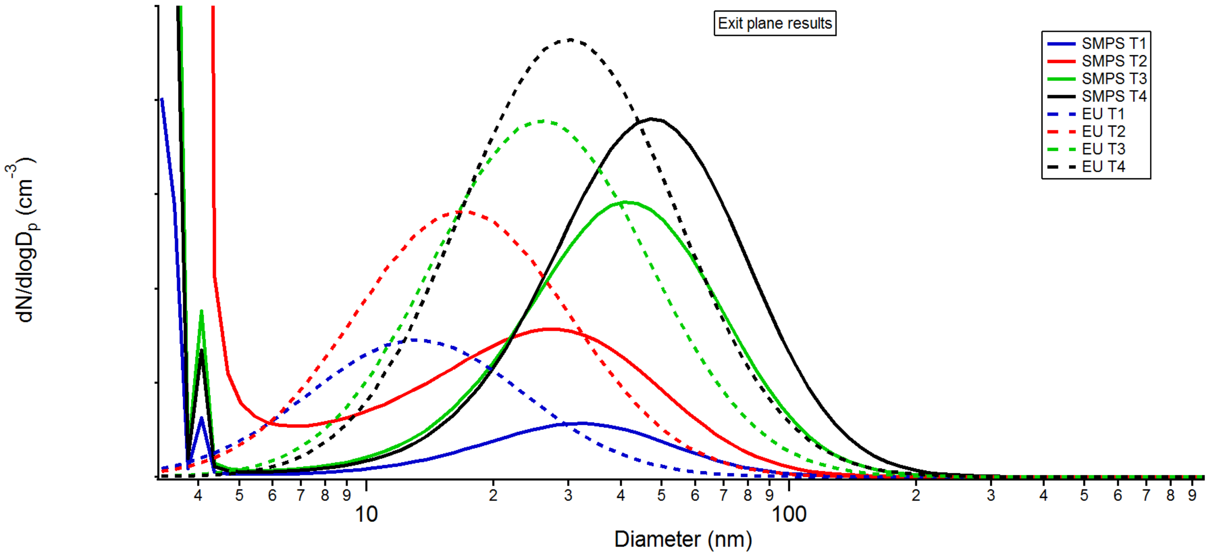

Figure 51 SMPS and EU/EASA predicted engine exit plane distributions.

The first and most notable result is that the SMPS predicted distributions all have modal diameters larger than those predicted by the LLCA. Furthermore, the modal diameters are all greater than 20 nm. However, what is also evident from the data is the effect of the line loss corrections at small sizes. The fitted SMPS distributions do not fall to zero at ~3.28 nm, the smallest size used in the methodology. This is producing large artefacts in the predicted SMPS engine exit plane data. It would be possible to improve the fits to the measured data by forcing the fits to zero and removing the unrealistic data.

Table 11 below summaries the DGN, facn and facm predicted when using the SMPS data in the EU/EASA line loss models. The numbers from the EU/EASA system are also included for comparison. Because of the effects of the line loss at small sizes, facn or facm > 3.28 nm is not realistic, but facn or facm > 5 nm is. However, the line loss functions have a substantial effect on T2 (highlighted in red) and should not be used. This is because T2 data has the smallest DGN and a large tail extending to small sizes (see Figure 51).

Table 11 Summary of DGN, facn and facm with SMPS

Test point	SMPS	EU/EASA	SMPS	EU/EASA	SMPS	EU/EASA
	DGN (nm)		Facn > 10nm		facn > 5nm	facn > 3.28nm
T1	30.0	13.1	2.83	5.46	2.93	7.99
T2	26.7	16.9	3.18	4.47	3.64	5.48
T3	40.6	25.9	2.48	3.26	2.52	3.44
T4	46.4	30.1	2.34	2.96	2.36	3.06
			Facm > 10nm		facm > 5nm	facm > 3.28nm
T1			1.41	1.61	1.41	1.63
T2			1.42	1.53	1.42	1.53
T3			1.39	1.43	1.39	1.43
T4			1.38	1.41	1.38	1.42

It can be seen that facn does not change much with the lower size limit for the SMPS data, indicating that most of the particles are larger than 10 nm. Furthermore, there is less variation in facn with power setting. This is because the measured modal diameter and hence DGN at the engine exit plane lie on the section of the penetration curve that does not change significantly with size. The value of SMPS facn is also lower than facn as predicted by the EU/EASA system. This is because the modal diameter from the SMPS is larger than that predicted by the EU/EASA LLCA. Therefore there is less correction (i.e amplification) to the SMPS data and hence the corrected total number (area under the SMPS curves in Figure 51) is less than the LLCA total number. In other words, the engine exit plane predicted number is less when using the measured SMPS data when compared with the APC and LII data measured on the EU/EASA system (using the LLCA).

The values of facm were calculated by converting the SMPS number-size distribution to mass, assuming a density of 1 g/cm^3, and then summing up the total mass. However, before summing the total mass, the VPR loss function must be applied to the SMPS number distribution data. This is because the mass as measured by the LII is recorded at 5PTS, which is before the VPR. In the same way as the number comparisons, the modelled SMPS mass distribution can be compared to the modelled LLCA mass distribution. The comparison for T1 and T4 are shown below in Figure 52 and Figure 53 respectively.

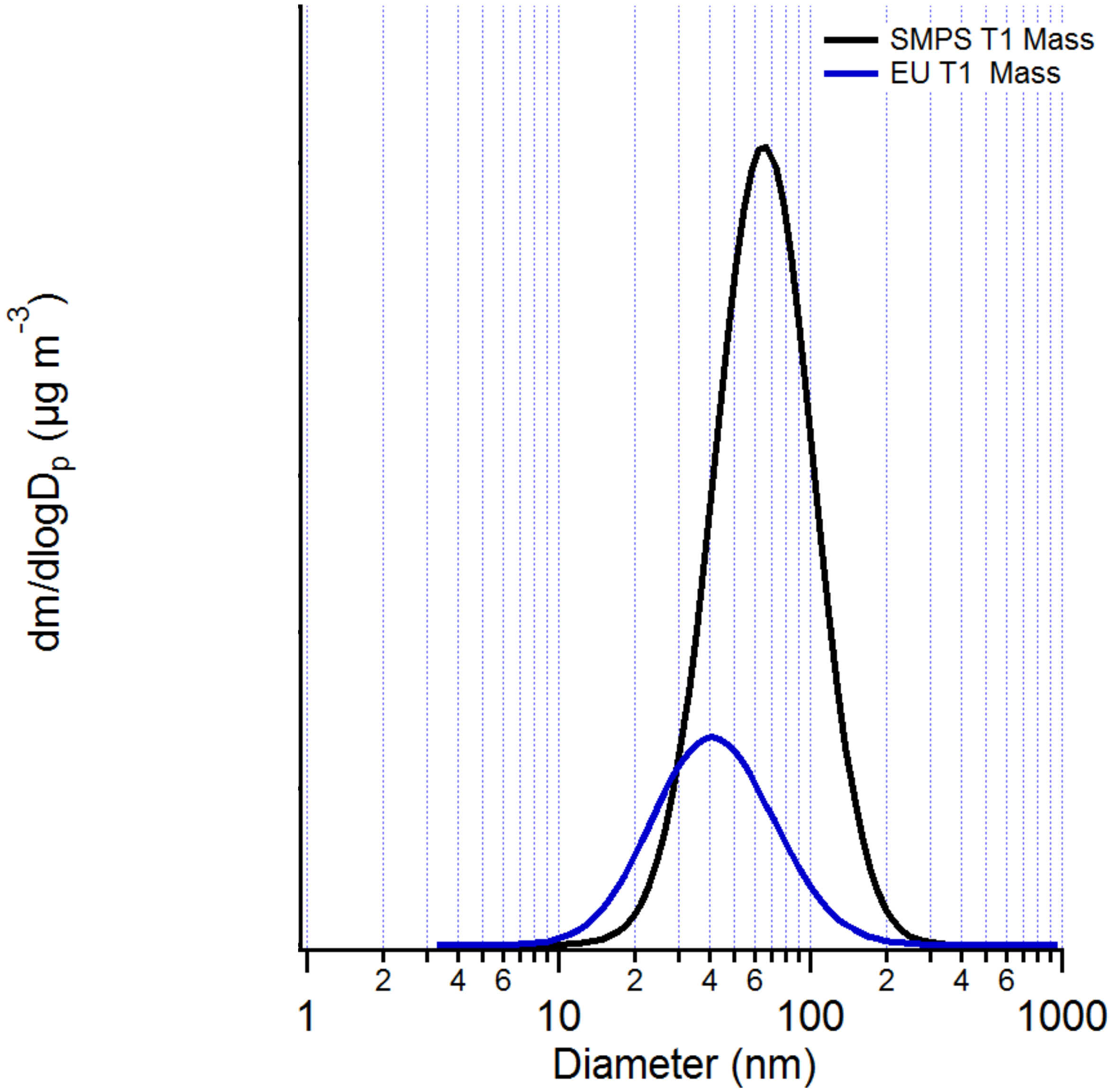

Figure 52 Mass distributions for T1 using the SMPS number distributions converted to mass and LLCA results based on the APC and LII data.

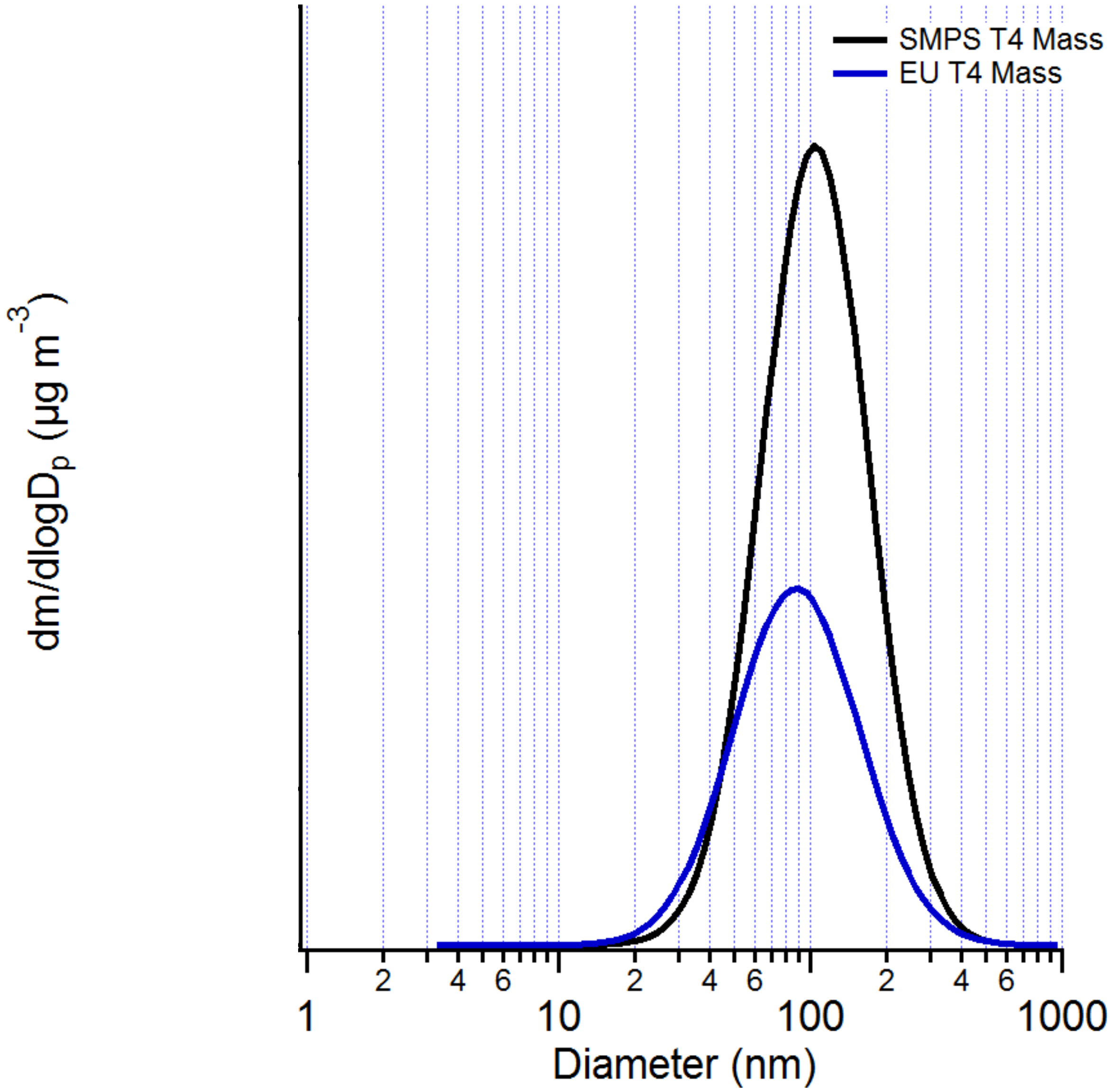

Figure 53 Mass distributions for T4 using the SMPS number distributions converted to mass and LLCA results based on the APC and LII data.

As with previous discussions, absolute mass cannot be reported, but the percentage difference ((EU-SMPS)/EU) for T1 to T4 are: -205.5 %; -103.6 %; -86.5 % and; -94.5 % respectively. The conclusion drawn from this data is that the total, predicted SMPS mass is significantly higher than the measured mass, assuming a density of 1 g/cm^3 and sigma of 1.8. Inspection of the graphs indicates that the falling edge of the distribution are all tending to zero, so it is unlikely that there is an artefact in the data being produced by the SMPS fits, as there was with the number distribution at the rising edge of the distributions.

7.5.4 Line loss correction for Small helicopter engine (SC03 data)

The data presented here is a revised version of the small helicopter engine dataset from the SAMPLEIII SC03 report. The revisions include using the improved EU/EASA VPR loss model and an improvement in the model for the line loss, which now contains the temperature of the probe inlet (for thermophoretic loss). Figure 54 below shows the total line loss for the system at the APC at two engine settings, which represent the extremes in temperatures and hence the largest differences in thermophoretic losses. Although a total of 7 data points were taken, the values recorded in the 10,000 – 19,000 RPM range are very similar, so 13,000 RPM was chosen to represent these points.

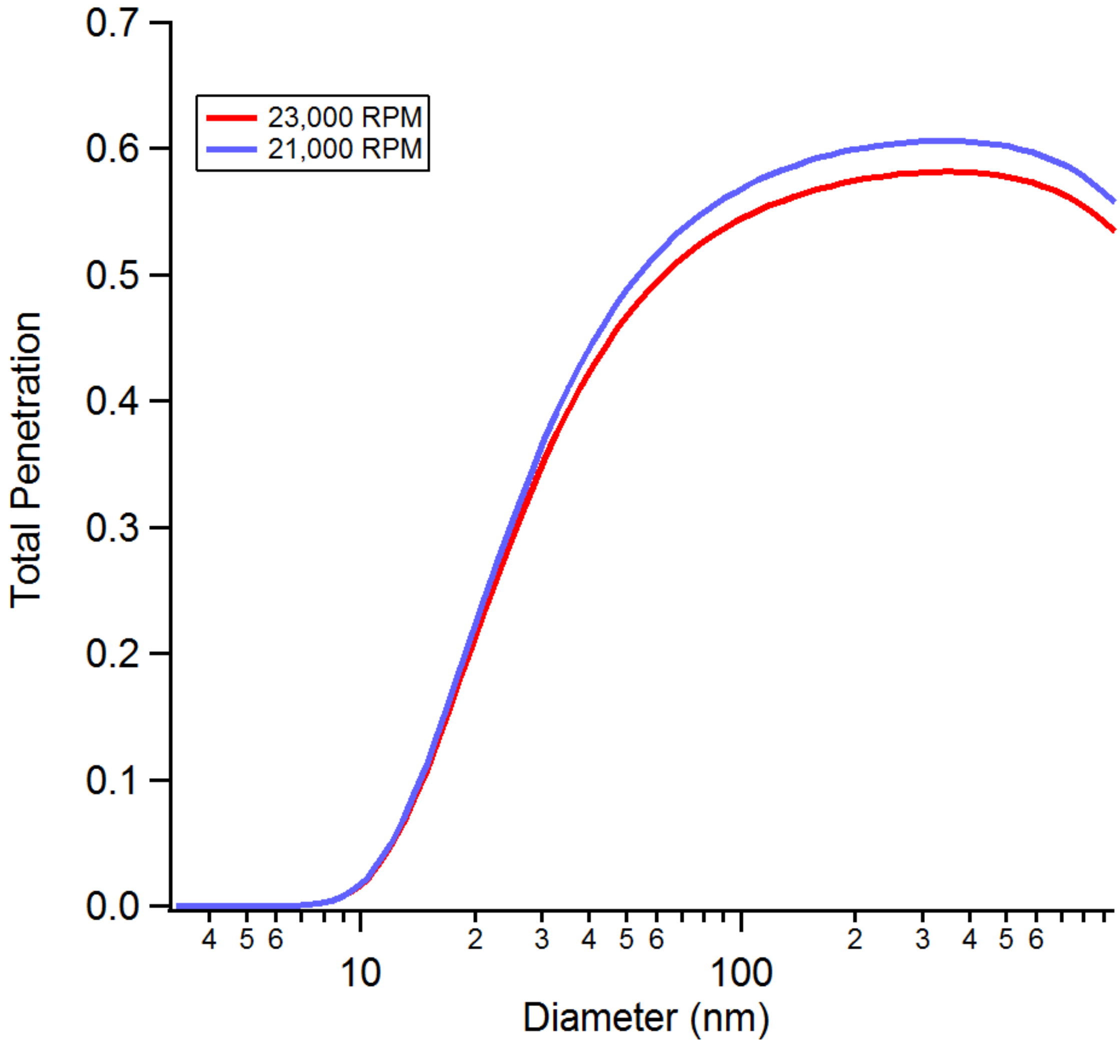

Figure 54 Total line loss at 23k and 21k RPM.

An SMPS was also attached to the exhaust of the APC similarly as in section 6.3.1.3. The raw and fitted distributions are shown below, which were corrected for DF1 and VPR DF2.

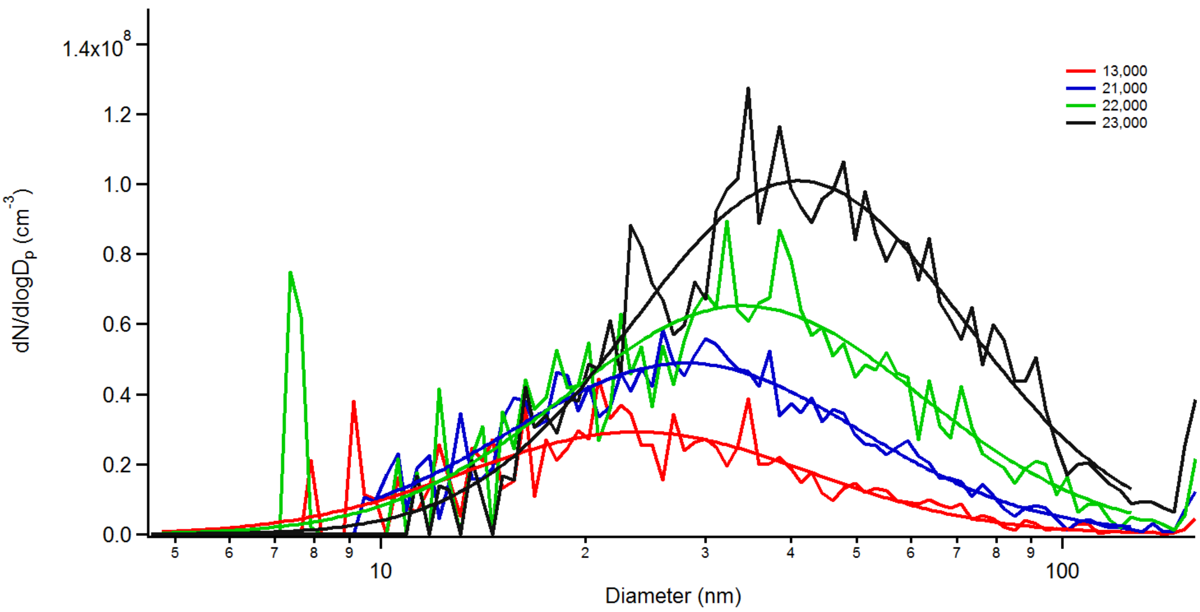

Figure 55 Measured raw and fitted SMPS distributions, corrected for DF1 and VPR DF2.

As with the data from section 7.3.1, the SMPS data shows little evidence of particles below 10 nm. At small sizes, there is a low probability of observing a particle with the SMPS, so any particle detected is subjected to large corrections in the SMPS software. This leads to poor counting statistics and noisy data. The data shown here represents an average of 2 or 3 scans due to the time limitations in sampling. More scans would reduce the noise in the data. The lack of any particles below 7 to 8 nm is consistent with data from previous SAMPLEIII SC02 and SC03 campaigns, although there is a scarcity of data available, generally, from similar tests. However, it must be noted that the mathematical fits to the data are still producing non-zero data at Dp < 5 nm, the effects of which are presented below and are consistent with the results and impacts from the lean burn staged engine.

In addition to the DF1, VPR DF2 and system penetration, the SMPS data was further corrected for the sample line losses connecting the SMPS inlet to the exhaust of the APC and scaled by the ratio of the SMPS total number : APC total number. This is the same procedure as used for the lean burn staged engine.

7.5.4.1 *Small helicopter engine results – facn, facm and DGN*

The results from the Small helicopter engine are presented below in Table 12 and Figure 56. Table 12 has all 4 data points in whilst Figure 56 just shows 13,000 and 23,000 RPM which have the extremes in DGN. The first observation is that the modelled DGN are generally smaller than the ones modelled for the lean burn staged engine, with the smallest DGN below 10 nm at 6.34 nm. This raises the question of whether the modelled data is physically realistic or simply a product of mathematics.

Current combustion understanding is that soot particles (nvPM) do not exist smaller than 10 nm. nvPM is produced in rich combustion flames and then burnt off in the downstream part of the combustion system at leaner but still hot conditions. The burning off of soot within the combustor is a function of the particle size and it proceeds more rapidly as the soot size reduces. Thus small (<10 nm) soot particles are not recognised to physically exist at a gas turbine engine exit.

The LLCA analysis applies the penetration functions to the data, without knowledge of whether the outputs are physically feasible. Once again, the line loss functions are having a large impact at the smallest sizes. For example, as can be seen from both the table and the graph, 23,000 RPM has more particles recorded at the APC than the 13,000 RPM setting, yet the line loss corrections are predicting much higher concentrations at the exit plane for the 13,000 RPM setting because the modelled diameters are smaller at 13,000 RPM.

Table 12 Results from the LLCA for the Small helicopter engine.

RPM ('000)	APC (P/cm^3)	LII (µg/m^3)	DGN (nm)	Dp > 10nm: Total N exit (P/cm^3)	Dp > 10nm: Total M exit (µg/m^3)	Dp > 10nm: facn	Dp > 10nm: facm	Dp > 3.28nm: Total N exit (P/cm^3)	Dp > 3.28nm: Total M exit (µg/m^3)	Dp > 3.28nm: facn	Dp > 3.28nm: facm
13	2.31e7	263	6.34	2.21e8	534	9.53	2.04	8.88e8	636	38.3	2.42
21	3.65e7	986	16.9	1.99e8	1596	5.46	1.62	2.94e8	1618	8.05	1.64
22	4.95e7	2446	18.3	2.09e8	3712	4.22	1.52	2.46e8	3722	4.97	1.52
23	7.41e7	6627	24.3	2.58e8	9789	3.48	1.48	2.75e8	9794	3.72	1.48

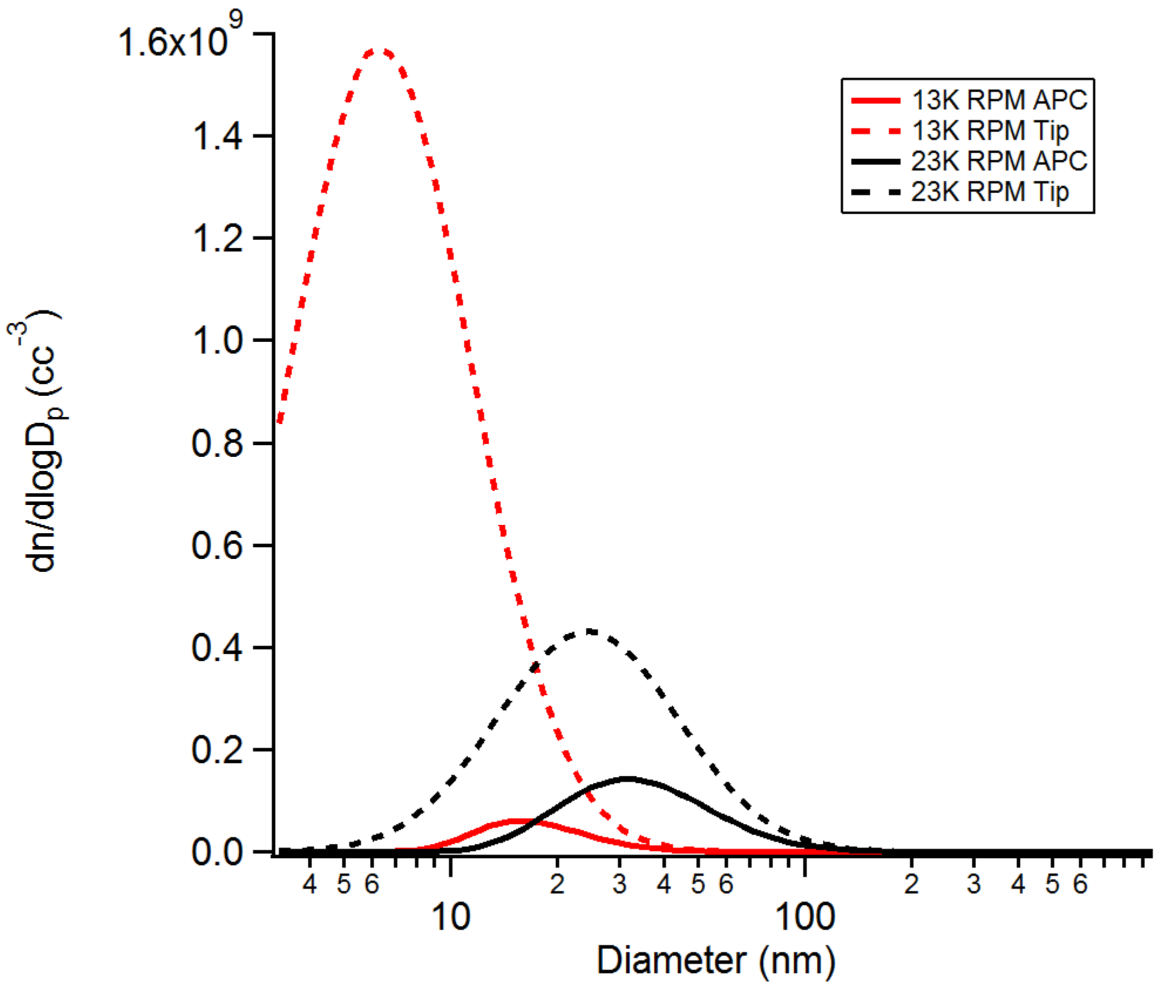

Figure 56 SMPS and LLCA size distributions for 13 K and 23 K RPM

If the results from the 13,000 RPM setting are correct, then the facn (and to a lesser extent facm) are under estimated. The smallest size in the solver routine is 3.28 nm. It is clear the distribution is non-zero at this size, suggesting there are particles below this size. This seems extremely unlikely based on current gas turbine combustion theory for nvPM emissions.

Another observation of the results is that the concentrations at the tip are all of the order 1e8 P/cm^3 or higher. This puts the particles in the regime where coagulation could be having an effect, (Barouch et al., 2012[a]). The work cited predicts that at concentrations at 1e8 P/cm^3, 50 nm particles would be reduced in concentration by 23 % in 3 s with a small increase in overall size. The effects of agglomeration are not included in current models as it is believed the engine exit probe tip inlet particle concentrations are below 1e8 P/cm^3.

7.5.4.2 *Small helicopter engine - measured vs modelled data*

The SMPS size distributions as measured at the APC inlet are shown below in Figure 57, along with the modelled distributions from the LLCA analysis. The results show the same overall trend as the lean burn staged engine results: the measured modal diameter is greater than the predicted modal diameter from the LLCA.

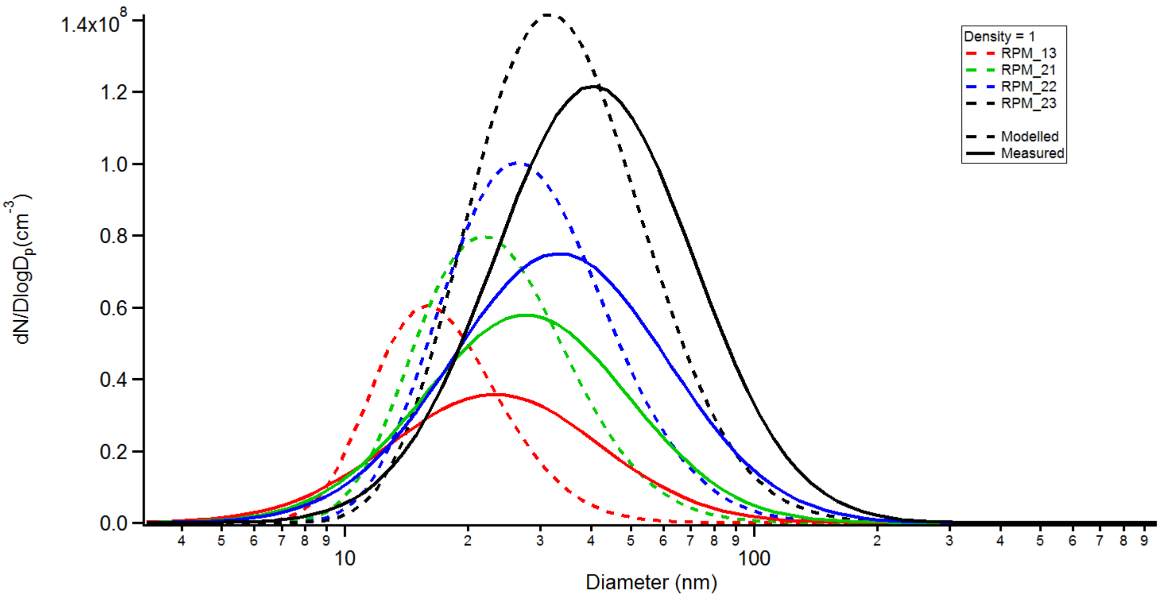

Figure 57 Measured and modelled distributions at the APC inlet

As with the lean burn staged engine, the larger measured modal diameter means the convolved number to mass distributions from the SMPS produce much higher total mass, at density = 1 g/cm^3, than the reported values from the LII. This is shown in Figure 58 below.

[a] Barouch et al. Sampling of non-volatile vehicle exhaust particles: A Simplified Guide. SAE International, DIO: 10.4271/2012-01-0443. 2012

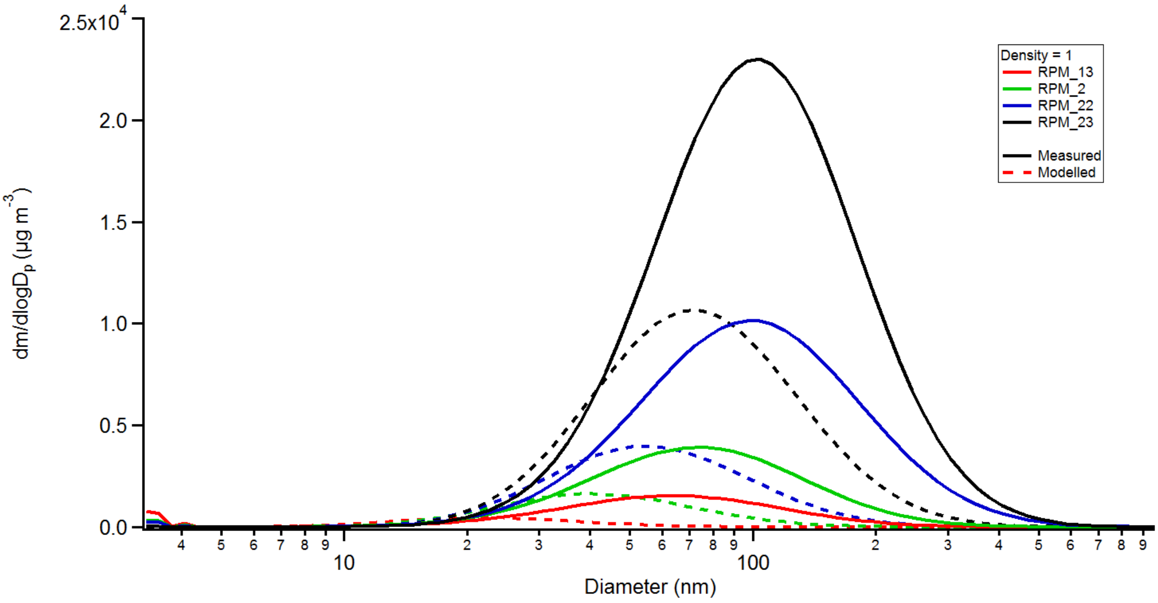

Figure 58 Mass distributions from the LLCA model and convolved SMPS number distributions.

The SMPS distributions can be used to predict the engine exit plane number and mass concentrations. An example of this is shown below in Figure 59 for the 13,000 RPM setting.

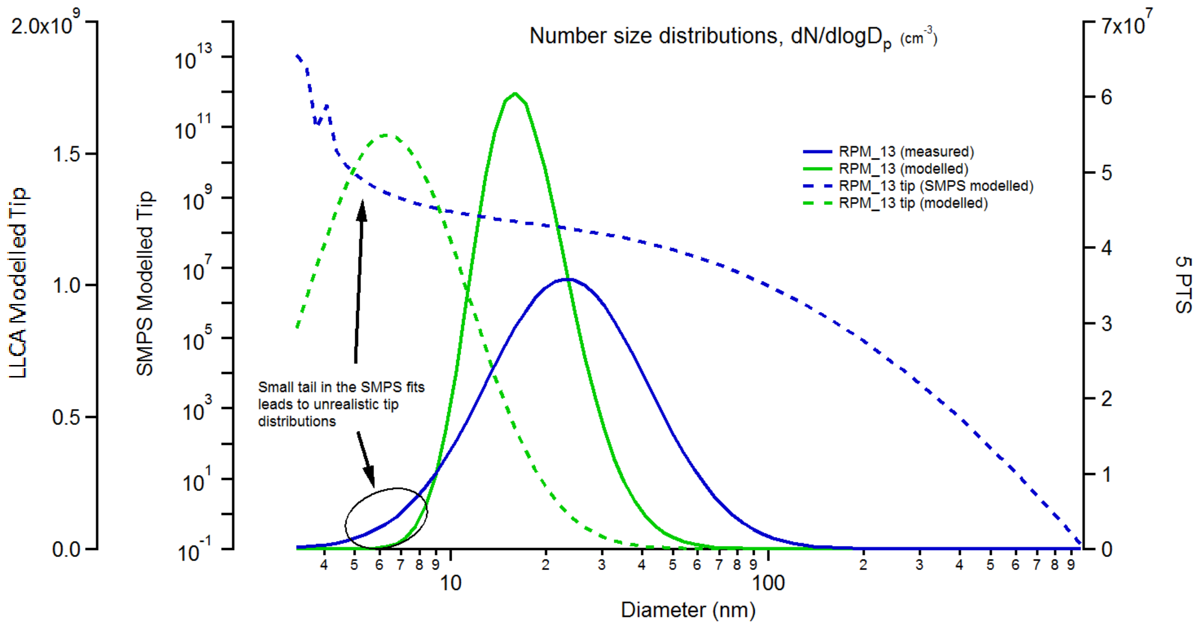

Figure 59 Comparison of the number size distributions at the 13,000 RPM engine setting using both LLCA model and SMPS data. The RPM_13 tip (SMPS modelled) is obtained by using the measured SMPS data at 5PTS and applying the line loss corrections to it.

This shows the effect of the mathematical fits and the large line loss functions combined. The small tail in the SMPS fit is being multiplied up by orders of magnitude making the determination of facn, facm and DGN impossible. This is the same for the 21,000 and 22,000 RPM settings as well. Some reasonable information can be determined from the 23,000 settings. The data for the 23,000 setting is shown below in Figure 60.

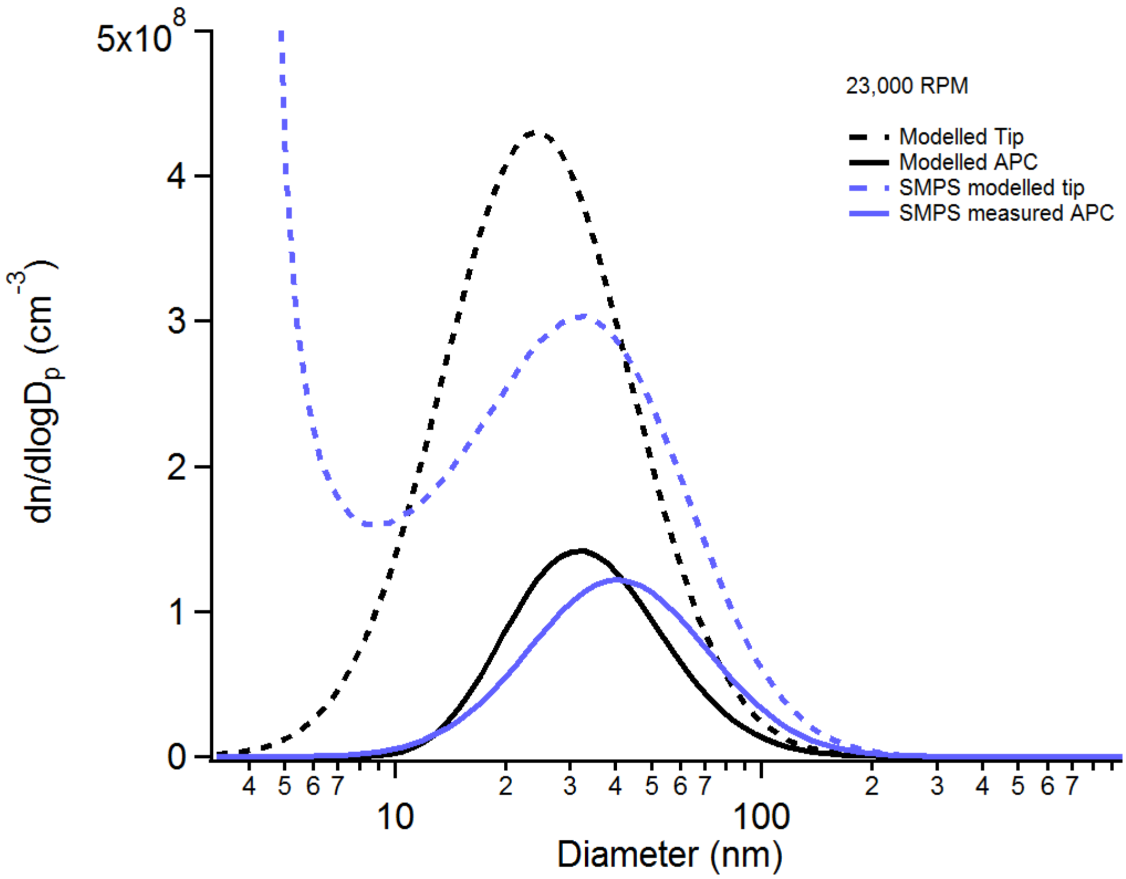

Figure 60 Comparison of the number size distributions at the 23,000 RPM engine setting using both LLCA model and SMPS data. The SMPS modelled tip is obtained by using the measured SMPS data (SMPS measured APC) at 5PTS and applying the line loss corrections to it.

The graph shows that the predicted DGN (SMPS modelled probe tip) is approximately 30 nm and is larger than the predicted diameter from the LLCA (modelled probe tip), based on the measured number and mass, consistent with the lean burn staged engine results. However, in all cases, the effects of the penetration functions means that the facn and facm (and for the other settings, DGN) for the SMPS data cannot be determined.

7.5.5 Effects of density and sigma

Throughout the analysis, there have been certain parameters used which have been assumed to be constant and have not been varied. The first is the density, which has been fixed at 1 g/cm^3 and the second is the width of the log-normal distribution at the exit plane, σ, which is set to 1.8. The values are generally accepted as being representative of combustion nvPM. Varying these factors may provide a means of improving the comparison between measured and modelled results.

7.5.5.1 *Changing the effective density, ρ_{eff}*

It is important to recognise that unless the particles are perfectly spherical and consist of a homogeneous material, then the prescribed density (ρ) is in fact the effective density (ρ_{eff}), which is a function of the material density and the dynamic shape factor. Effective density has several different definitions in the literature and depends on what instruments are used to measure it. DeCarlo et al[a]., summarises the three main definitions and shows the differences between them as a function of the dynamic shape factor (χ). The dynamic shape factor is the ratio of the drag forces on the particle with diameter D_p to the drag forces on an equivalent spherical particle with diameter D_{ve} that has the same total volume as the particle being measured. For perfectly spherical particles, the dynamic shape factor = 1 and $D_{ve} = D_p$; and if the material density = 1, then $\rho_{eff} = \rho$. Figure 61 and Figure 62 show the effects of changing the effective density to 0.55 g/cm^3 on the small helicopter engine data for both number and mass.

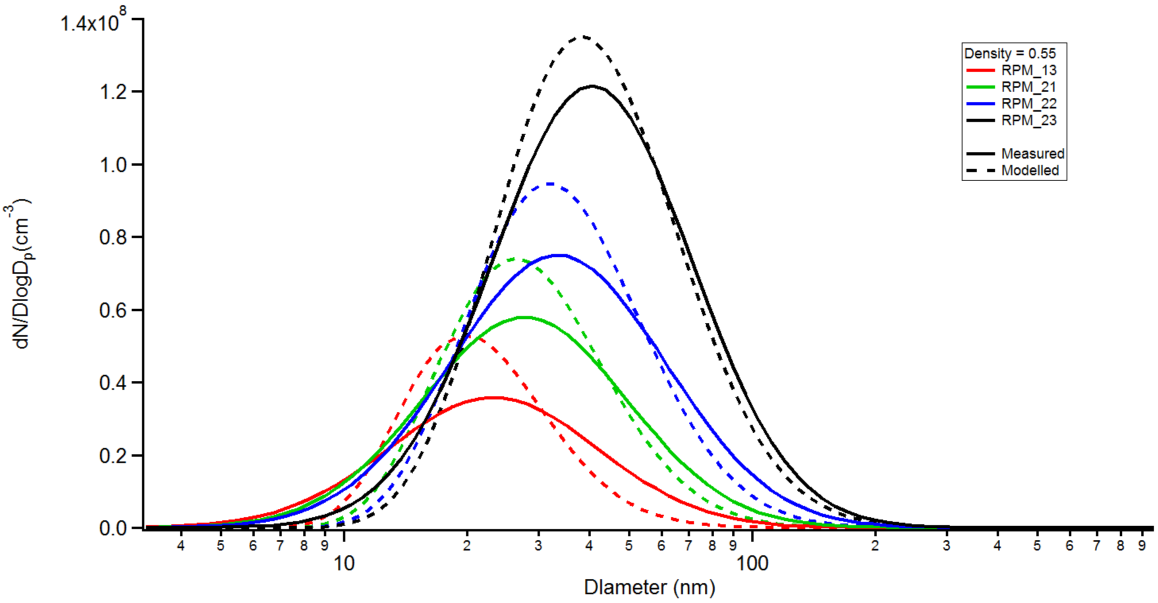

Figure 61 SMPS measured and LLCA modelled APC number distributions at ρ_{eff} = 0.55 g/cm^3

[a] Peter F. DeCarlo, Jay G. Slowik, Douglas R. Worsnop, Paul Davidovits, and Jose L. Jimenez, "Particle Morphology and Density Characterization by Combined Mobility and Aerodynamic Diameter Measurements. Part 1: Theory", AS&T 2004

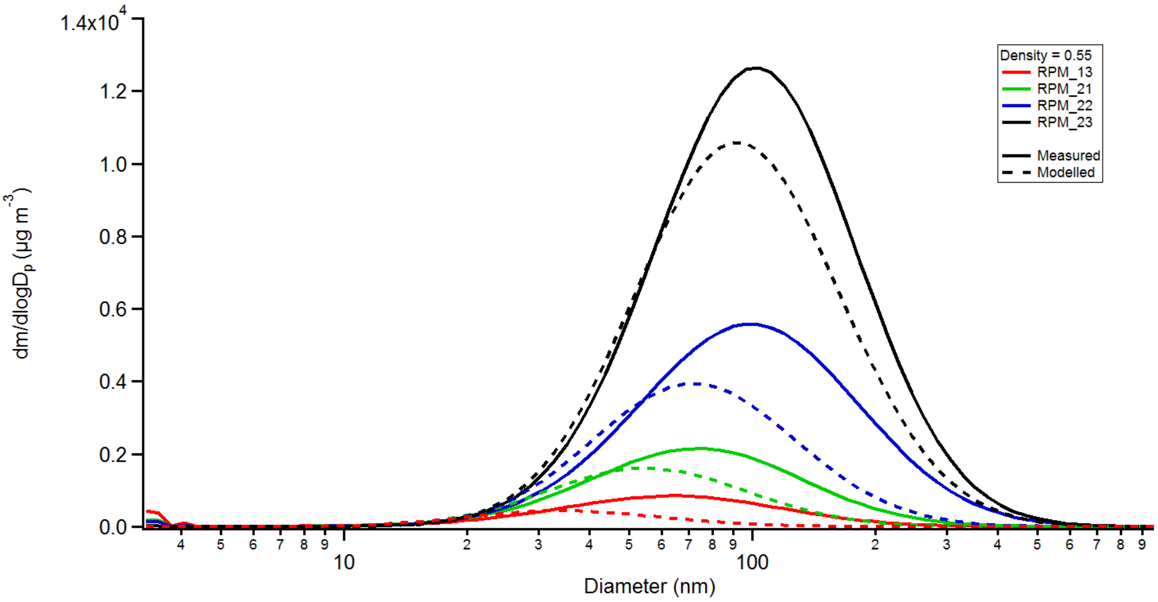

Figure 62 SMPS modelled and LLCA modelled LII mass distributions at ρ_{eff} = 0.55 g/cm^3

Changing ρ_{eff} has improved the agreement between measurements and modelling for both the mass and number from the LLCA and the distributions from the SMPS. Whilst they are not in complete agreement, the differences are significantly less. It is noteworthy that the agreement is better when the modal diameter is larger. This could be in part due to the line loss functions, but it could also indicate that a size dependant ρ_{eff} may be more effective. The use of ρ_{eff} here is not complete, as there are effects on particle size which have not been implemented. These are discussed below in section 7.5.7.2.

Using the assumption that ρ_{eff} = 0.55 g/cm^3, the effects on the modelled engine exit plane concentrations and distributions can be investigated. These are shown below in Figure 63 for 13,000 and 23,000 RPM and Table 13 for all settings (for Dp > 10 nm).

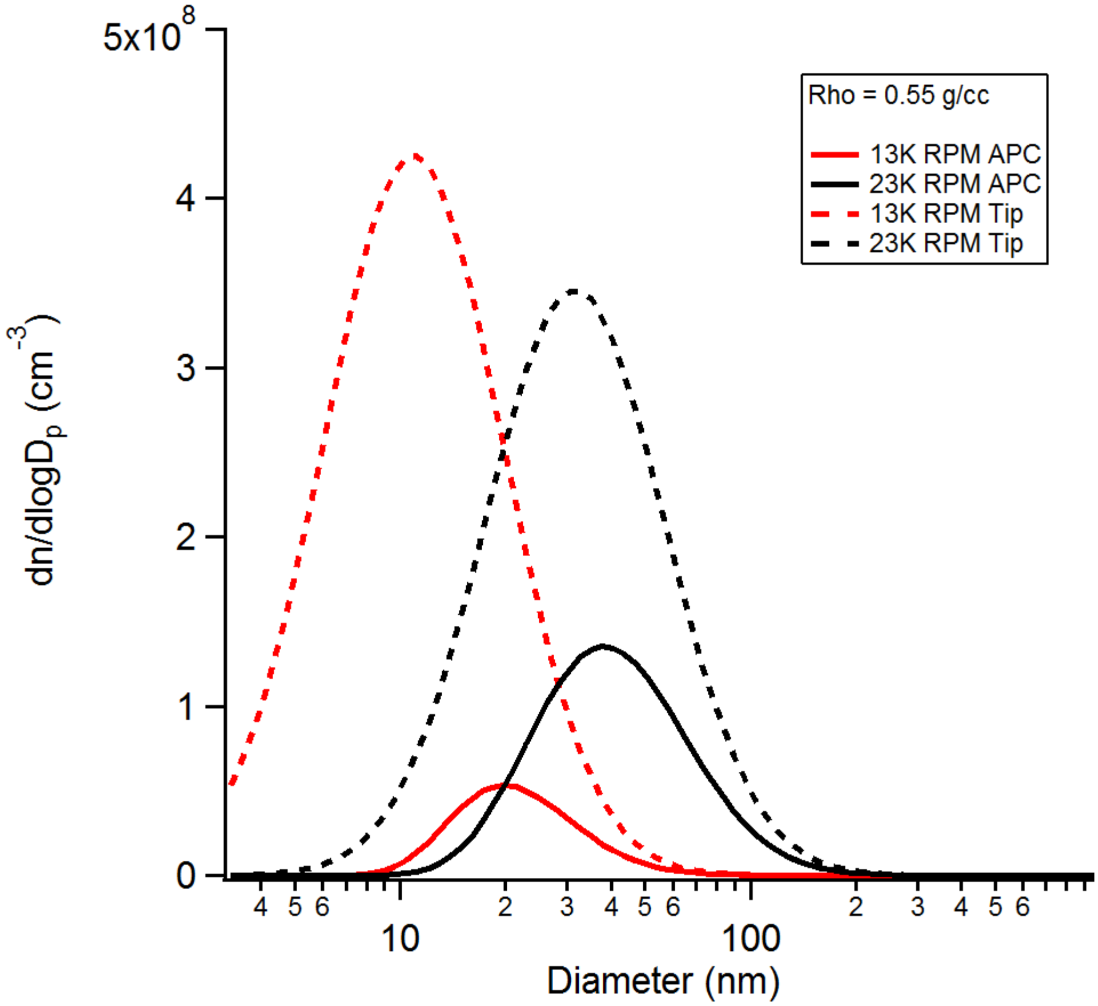

Figure 63 Modelled Exit plane and APC distributions at ρ_{eff} = 0.55 g/cm^3

Table 13 Facn, Facm and DGN results for ρ_{eff} = 0.55 g/cm^3 for Dp > 10nm.

RPM	APC (P/cm^3)	LII (µg/m^3)	DGN (nm)	Total N exit (P/cm^3)	Total M exit (µg/m^3)	facn	Facm
13,000	2.31e7	263	10.9	1.52e8	465	6.54	1.77
21,000	3.65e7	986	18.2	1.52e8	1472	4.16	1.49
22,000	4.95e7	2446	24.3	1.67e8	3519	3.38	1.43
23,000	7.41e7	6627	31.5	2.16e8	9440	2.91	1.42

The data shows that by allowing the ρ_{eff} to decrease the predicted DGN are larger than for ρ_{eff} = 1 g/cm^3. This makes the results more physically realistic in line with current combustion theory. However, the predicted engine exit plane concentrations are still greater than 1e8 P/cm^3, which would indicate that coagulation is potentially affecting the data, but not accounted for in the LLCA. This further highlights the need to validate the line loss functions.

7.5.6 Relationships between DGN, exit plane N, σ and ρ_{eff}.

As well as varying the ρ_{eff}, the assumed width of the log normal exit plane distribution, σ, can be varied. The combination of both affects the engine exit plane total number and DGN in the LLCA model. Figure 64 below illustrates these effects within the LLCA model by varying the ρ_{eff} from 0.55 to 1.2 g/cm^3 and σ from 1.6 to 1.85. The data is taken from T4 from the lean burn staged engine. The number concentration has been normalised to protect proprietary information.

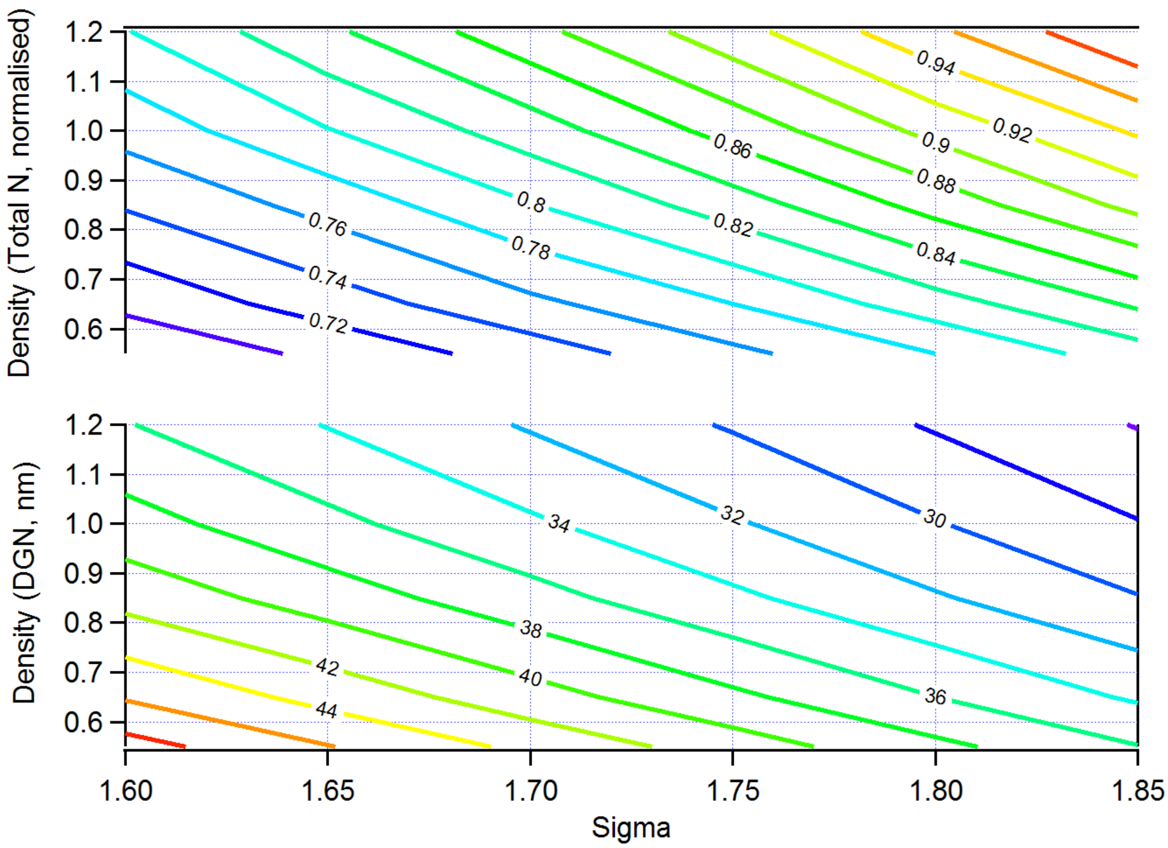

Figure 64 Variations in total exit plane number concentration and DGN for T4.

The results are shown in the form of contours plots. The bottom plot is the DGN and the top plot is the total number at the exit plane, normalised to the largest value. For a fixed ρ_{eff}, as σ increases there is a decrease in the DGN. This leads to an increase in the total number of particles for the same fixed density. Similarly, for a fixed sigma, as you increase the density you decrease the DGN and therefore increase the total number. The combination of DGN, ρ_{eff} and σ ensure the modelled total number and mass at 5PTS agrees with the measured data.

7.5.7 Effects on particle size

Throughout the report and in the LLCA, a particle diameter is reported. For spherical particles, it is easy to define the particle diameter. However, the particles produced from combustion sources are rarely spherical. The degree of non-sphericity generally increases with decreasing size. When particles are non-spherical, an equivalent diameter needs to be reported. This equivalent diameter depends on the instrument used to measure the particle. Below are TEM images from Bois et al.[a], obtained during SAMPLE III SC02 at the exit of the EU/EASA sampling system, and are therefore representative of aircraft particles sampled using an AIR6241 sampling system.

These particles were size selected by a SMPS onto the TEM grid. Figures a and b are 15nm particles, figure c 50nm. It is clear these particles are not spherical. The particles from a SMPS or DMS are said to have a equivalent mobility diameter, D_m. The mobility diameter is defined as the diameter of a sphere with the same migration velocity across a constant electric field as the particle being measured.

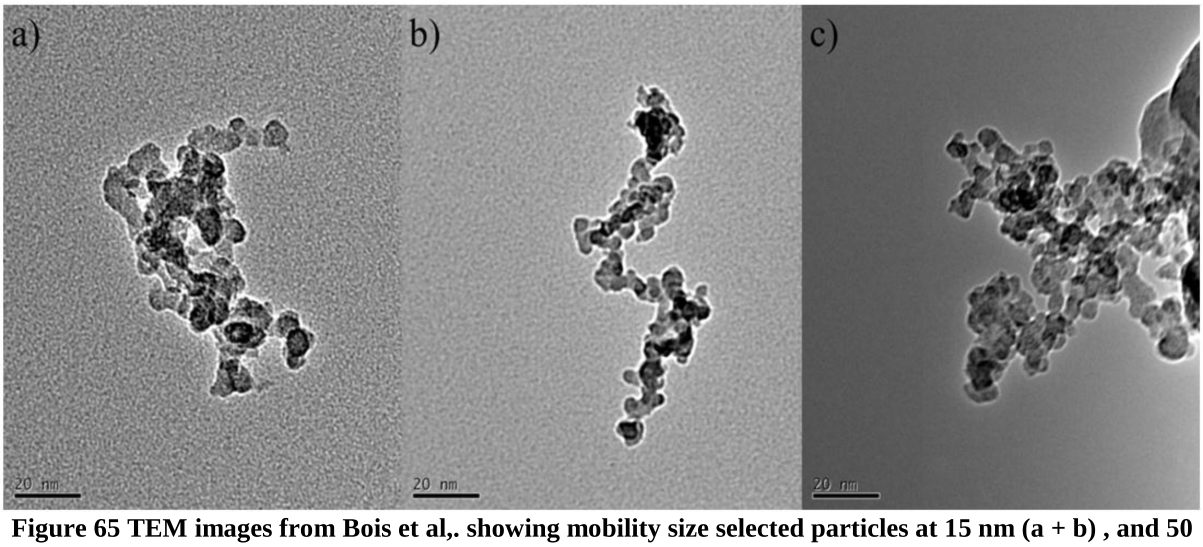

Figure 65 TEM images from Bois et al,. showing mobility size selected particles at 15 nm (a + b) , and 50 nm (c)

[a] Adam M. Boies, Marc E. J. Stettler, Jacob J. Swanson, Tyler J. Johnson, Jason S. Olfert, Mark Johnson, Max L. Eggersdorfer, Theo Rindlisbacher, Jing Wang, Kevin Thomson, Greg Smallwood, Yura Sevcenco, David Walters, Paul I. Williams, Amewu A. Mensah, Ramin Dastanpour and Steven N. Rogak, "Particle Emission Characteristics of a Double Annular Combustor Gas Turbine". *Manuscript submitted to Aerosol Science & Technology, November 2014*

7.5.7.1 *LLCA and SMPS data*

The LLCA theoretical particle distributions are based upon information obtained from DMS measured aircraft exhaust data, and are therefore reporting mobility diameters, D_m, and should be directly comparable to the SMPS data. The conversion to mass uses the effective density term to convert the diameter to the volume equivalent diameter, D_{ve}. This was introduced in section 7.5.5.1. The most common explanation of D_{ve} in the literature is to imagine the particle of interest, such as those in Figure 65 above, is melted down to a liquid and then formed into a sphere. The diameter of that sphere is the D_{ve}, as it has the same total volume as the original particle. This is required because the LII measures soot volume fraction and reports mass based on a particle material density; therefore any reported diameter should have the same total volume excluding any internal voids as the LII measured particles. There is a relationship between D_m and D_{ve} given by:

$$\frac{D_m}{C_C(D_M)} = \frac{D_{Ve}.\chi}{C_C(D_{ve})}$$

Equation 2

Where χ is the dynamic shape factor and $C_c(D_m)$ and $C_c(D_{ve})$ are the Cunningham slip correction factors at values D_m and D_{ve}. However, χ is not explicitly defined. If ρ_{eff} is changed, and by inference χ, this may require modification of the assumed engine exit plane log-normal distributions.

7.5.7.2 *Particle properties and the UTRC line loss model*

There are potentially some issues arising from the UTRC treatment of particle line loss. The UTRC model considers losses due to inertial impaction, bends, diffusion, thermophoretic losses and electrostatic losses, which requires knowledge of the particle diameter. As the particles are likely to be non-spherical, an equivalent diameter should be used.

For inertial impact in bends, the equivalent aerodynamic diameter should be used, D_a. For diffusional losses, Hinds argues that the physical diameter, D_p, should be used. Whilst Baron and Willeke suggest the diffusive diameter should be used. The relationship between different particle diameters are functions of the dynamic shape factor and for D_a, the particle density.

The UTRC treatment of particle loss uses the same diameter base across all sizes. Work is needed to investigate whether using a constant diameter base is appropriate. This could impact the facn, facm and DGN calculations.

This is also true for both the VPR penetration and CPC efficiency calibration. Both calibrations use a SMPS to size select the particles sampled by the instrument, and therefore reports penetrations or counting efficiency in mobility space. If the shape of the calibration particles are different to the engine particles, the corrections will be applied at the wrong particle size (Equation 2).

7.6 Conclusions of Task 2c

1) For the lean burn staged engine, two distinct nvPM regimes were observed: pilot only mode, similar to in-production rich burn; and the much lower emissions were observed at the staged mode, four orders of magnitude lower for number and three orders of magnitude lower for mass.

2) The lean burn staged engine results were similar to engine inlet ambient concentrations and also around the instruments' limit of detection.

3) For both mass and number the lean burn staged engine conditions produced instrument inlet concentrations which were lower than the AIR6241 instrument calibration levels (<10 µg/m^3; <1e3 P/cm^3) which increases the overall measurement uncertainty.

4) The inter-comparison of the nvPM systems (RR and EU/EASA) for Emissions Index number (EInum) for both the lean burn pilot only and the in-production rich burn engines, showed consistency with previous SAMPLE III SC02 and SC03 studies. Namely that the variability is within the E31 estimated ±25 % uncertainty. It should be noted that this study is the first time different number measurement instrumentation was compared and that the uncertainty has not increased.

5) The inter-comparison of the nvPM systems (RR and EU/EASA) for Emissions Index mass (EImass) for both the lean burn pilot only and the in-production rich burn engines, showed consistency with previous SAMPLE III SC02 and SC03 studies. Namely that the variability is within the E31 estimated ±25 % uncertainty.

6) Some measurements for both mass and number were close to the instrumentation level of detection. High variability (>± 25%) was observed, which is consistent with previous studies.

7) It can be seen that absolute variability of EImass and EInum is dependent on the EImass and EInum data level.

8) Inter-comparison of the RR and EU/EASA nvPM analysers only showed that intra-system variability was reduced to ±6 % and ±9 % for EInumber and EImass respectively. This shows that the sampling source variability is around ±10 to 20 % which is consistent with SAMPLEIII SC02 findings.

9) A Limit of Quantification (LOQ) could be established using standard deviation and the PMTG acknowledged maximum uncertainty level (e.g. ± 25 %). It is recommended that 2sigma deviation should be reported with nvPM data to help provide data for a possible LOQ calculation. Further statistical work is required to verify an LOQ limit, for example performing normality tests on individual data points as well as statistically testing repeated datasets.

10) Both nvPM systems were operability compliant to AIR6241, whilst they were operating sequentially.

11) The primary Dilution Factor of both systems was capable of operating within the prescribed AIR6241 range for the specific probe/rake setup utilised.

12) Any bias of the CO_2 analyser is an important component of the uncertainty, reducing this could improve particle measurement uncertainty.

13) In order to reduce EInum variability, there is potential to reduce the uncertainty in VPR dilution factor (DF2) by accounting for penetration differences at different dilution settings.

14) An assessment of adding an additional 0.9 m length to 4PTS (25 m) shows negligible impact to both mass and number nvPM instrumentation for both nvPM systems, in agreement with the UTRC line loss model.

15) SMPS and DMS size measurements on the lean burn pilot only engine were monomodal and agreed well after particle transport correction. With DGNs within 4 % average variance. Across all conditions DGNs were witnessed between 30 to 50 nm.

16) For the lean burn staged measurements both size instruments were close to their limit of detection.

17) Size measurements showed negligible impact of the additional 4PTS line length used in the in-production rich burn engine test.

18) Comparison between the MSS and LII showed good agreement with a small 7% bias well within the expected uncertainty of calibration.

19) SC05 work on line loss corrections highlights the need to perform a full error analysis on the model, taking account of all uncertainties in the predicted line loss and measured data

20) It is vital that any line loss correction has reliable sampling system penetration and loss functions.

21) It is clear that the effects of the line loss increases with decreasing particle size.

22) There is a need to validate the VPR loss functions below 15nm (where the function is an extrapolation and not fitted to data), as they are having a significant impact on the reported results.

23) Engine exit plane concentrations predicted by the Line Loss Correction Analysis (LLCA) for the EU/EASA and RR systems vary between ~54 % to 123 % for number and ~13 % to 45 % for mass. Furthermore, physically non-realistic size distributions are sometimes produced. It needs to be understood whether these differences are within an acceptable experimental uncertainty or whether the LLCA does not represent the physical processes in the line.

24) For both the lean burn staged and Small helicopter engines, the LLCA predicted 5PTS distributions (mass and number) do not match the measured SMPS distributions with an assumed density of 1 g/cm^3, a sigma of 1.8 and an assumption of sphericity.

25) The SMPS always measures a larger diameter than predicted at the instruments. Consequently, the predicted exit plane total number using the SMPS data is lower than the LLCA model and the exit plane geometric mean diameter, (DGN) is larger.

26) The predicted mass from the SMPS assuming a density of 1 g/cm^3 is always larger than the mass measured by the LII.

27) Using an effective density (ρ_{eff}) of 0.55 g/cm^3 for the Small helicopter engine data improves the comparison between measured and modelled data for both number and mass. This result is consistent with the work of Hagen[a]. However, the analysis is not complete because the effect of shape may not have been applied correctly as the dynamic shape factor is unknown.

28) Using a size-dependent effective density could potentially improve the comparison between measured and modelled data for both number and mass.

29) Reducing ρ_{eff} increases the DGN for a given loss function. This may make results physically meaningful.

30) It is unlikely that particles are spherical, even at small sizes.

31) There is a need to check the correct particle diameter base is being used in the UTRC models because the particles are likely to be irregular shape in nature.

32) It is important to examine any fitted size distribution data as mathematical ‘tails’ at the small size will produce large artefacts when predicting exit plane distributions.

33) When predicted modal diameters are relatively large, where changes in penetration with size are small, the effects of changing the input values on DGN, facn (the fractional loss in number in the sampling system) and facm (the fractional loss in mass in the sampling system) are smaller than when the predicted modal diameters are relatively small, where there are significant changes in the penetration with size.

34) Further error propagation work needs to be performed to understand the amplified error impact on predicted engine exit concentration when either the mass and/or number instrument is below limit of quantification.

35) If either the mass or number instrument is below the limit of detection then the LLCA model will not provide an output and a different model methodology would need to be developed for predicting particle corrections for those engine data points. This would be an issue if the LLCA is used for certification methodology (for example, mixed vs unmixed engine exhaust sampling). The possible use of LLCA for airport emissions modelling needs to be assessed for these data points.

Specifically for the Small helicopter engine:

36) For both ρ_{eff} equal to 1 and 0.55 g/cm^3, the predicted number concentrations at the engine exit plane are of the order 1e8 P/cm^3, which is in the concentration range where coagulation could have an impact. If the loss functions are correct, the potential effects of this process need to be modelled to investigate the impact on DGN, facn and facm.

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[a] Hagen: “PM line loss correction without direct size measurement” 18th ETH conference on combustion generated nanoparticles, 2014.

8. Overall Conclusions

A summary of all of the conclusions from Tasks 1, 2a, 2b and 2c are presented below:

1) Drafting of the SAE E31 nvPM ARP has started with significant progress made via a number of drafts throughout 2014

2) The SAE E31 nvPM ARP is currently on schedule for early 2015. The ARP's delivery date will depend upon proof of robust measurement and operational testing of the proposed nvPM system by all engine manufacturers.

3) Further nvPM engine and laboratory testing will be required post-ARP ballot if a reduction in nvPM measurement uncertainty is needed by ICAO/CAEP/WG3/PMTG.

4) An additional user operability section has been added to the draft ARP and provided in time to be used for other inter-comparison test campaigns such as the US VARIAnT study.

5) The particle line loss correction methodology has been trialled using an existing SAMPLEIII SC03 dataset with issues identified and communicated back to SAE E31.

6) The EU/EASA nvPM system was fully calibrated and maintained for the system inter-comparison testing during SAMPLEIII SC05 to AIR6241 compliance

7) Calibration of equipment is time intensive (taking up to 6 weeks in the case of the AVL APC) and scheduling this in accordance with engine testing was difficult.

8) Dedicated training for operational staff and clear system operating procedures are required to ensure smooth operation of an nvPM measurement system. Specific small engine test training and the writing of standard operating procedures and checklists for the EU/EASA nvPM system has been performed.

9) Maintenance of the equipment has been simplified by having a dedicated operational staff; along with the benefit of improved design changes, brought upon by specific testing issues.

10) The primary Dilution Factor should be monitored over time (multiple test campaigns), as part of routine maintenance, to determine when the diluter nozzle orifice needs cleaning, however it is perceived that the newly installed back-purge facility will reduce this requirement.

11) Long term drift should be monitored of all nvPM instrumentation to establish the confidence level. Further effort is needed to work with instrument manufacturer's to change internal practices and provide "as found" calibration prior to instrument service maintenance procedures, as a routine to provide better understanding of instrument drift.

12) The dilution check for the VPR (DF2) is an important part of the nvPM system operability. Up to 10 % variability is allowed with values of 8 % being observed, for the lowest PCRF setting of 100. Reducing this variability could reduce overall nvPM EI uncertainty.

13) Two AIR6241 compliant nvPM systems (RR and EU/EASA) were successfully installed, operated and tested back-to-back on a lean burn staged engine across a wide range of engine power conditions

14) Two AIR6241 compliant nvPM measurement analyser systems (RR and EU/EASA) were successfully installed, operated and tested back-to-back on an in-production rich burn engine at two power conditions.

15) The possibility of installing, and therefore performing, a full sampling system inter-comparison is facility dependent. This will have an impact on the possibility of performing this specific test type in the future. However, different types (as detailed in the report) of system inter-comparison tests are beneficial and advantageous to SAE E31 to further assess and minimise sources of nvPM measurement uncertainty.

16) For the lean burn staged engine two distinct nvPM regimes were observed: pilot only mode, similar to in-production rich burn; and the much lower emissions were observed at the staged mode, four orders of magnitude lower for number and three orders of magnitude lower for mass.

17) The lean burn staged engine results were similar to engine inlet ambient concentrations and also around the instruments' limit of detection.

18) For both mass and number the lean burn staged engine conditions produced instrument inlet concentrations which were lower than the AIR6241 instrument calibration levels (<10 $\mu g/m^3$; <1e3 P/cm^3) which increases the overall measurement uncertainty.

19) The inter-comparison of the nvPM systems (RR and EU/EASA) for Emissions Index number (EInum) for both the lean burn pilot only and the in-production rich burn engines, showed consistency with previous SAMPLE III SC02 and SC03 studies. Namely that the variability is within the E31 estimated ± 25 % uncertainty. It should be noted that this study is the first time different number measurement instrumentation was compared and that the uncertainty has not increased.

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21) Some measurements for both mass and number were close to the instrumentation level of detection. High variability (>±25 %) was observed, which is consistent with previous studies.

22) It can be seen that absolute variability of EImass and EInum is dependent on the EImass and EInum data level.

23) Inter-comparison of the RR and EU/EASA nvPM analysers only showed that intra-system variability was reduced to ±6 % and ±9 % for EInumber and EImass

respectively. This shows that the sampling source variability is around ±10 to 20 % which is consistent with SAMPLEIII SC02 findings.

24) A Limit of Quantification (LOQ) could be established using standard deviation and the PMTG acknowledged maximum uncertainty level (e.g. ±25 %). It is recommended that 2sigma deviation should be reported with nvPM data to help provide data for a possible LOQ calculation. Further statistical work is required to verify an LOQ limit, for example performing normality tests on individual data points as well as statistically testing repeated datasets.

25) Both nvPM systems were operability compliant to AIR6241, whilst they were operating sequentially.

26) The primary Dilution Factor of both systems was capable of operating within the prescribed AIR6241 range for the specific probe/rake setup utilised.

27) Any bias of the CO_2 analyser is an important component of the uncertainty, reducing this could improve particle measurement uncertainty.

28) In order to reduce EInum variability, there is potential to reduce the uncertainty in VPR dilution factor (DF2) by accounting for penetration differences at different dilution settings.

29) An assessment of adding an additional 0.9 m length to 4PTS (25 m) shows negligible impact to both mass and number nvPM instrumentation for both nvPM systems, in agreement with the UTRC line loss model.

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35) It is vital that any line loss correction has reliable sampling system penetration and loss functions.

36) It is clear that the effects of the line loss increases with decreasing particle size.

37) There is a need to validate the VPR loss functions below 15nm (where the function is an extrapolation and not fitted to data), as they are having a significant impact on the reported results.

38) Engine exit plane concentrations predicted by the Line Loss Correction Analysis (LLCA) for the EU/EASA and RR systems vary between ~54 % to 123 % for number and ~13 % to 45 % for mass. Furthermore, physically non-realistic size distributions are sometimes produced. It needs to be understood whether these differences are within an acceptable experimental uncertainty or whether the LLCA does not represent the physical processes in the line.

39) For both the lean burn staged and Small helicopter engines, the LLCA predicted 5PTS distributions (mass and number) do not match the measured SMPS distributions with an assumed density of 1 g/cm^3, a sigma of 1.8 and an assumption of sphericity.

40) The SMPS always measures a larger diameter than predicted at the instruments. Consequently, the predicted exit plane total number using the SMPS data is lower than the LLCA model and the exit plane geometric mean diameter, (DGN) is larger.

41) The predicted mass from the SMPS assuming a density of 1 g/cm^3 is always larger than the mass measured by the LII.

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44) Reducing ρ_{eff} increases the DGN for a given loss function. This may make results physically meaningful.

45) It is unlikely that particles are spherical, even at small sizes.

46) There is a need to check the correct particle diameter base is being used in the UTRC models because the particles are likely to be irregular shape in nature.

47) It is important to examine any fitted size distribution data as mathematical ‘tails’ at the small size will produce large artefacts when predicting exit plane distributions.

48) When predicted modal diameters are relatively large, where changes in penetration with size are small, the effects of changing the input values on DGN, facn (the fractional loss in number in the sampling system) and facm (the fractional loss in mass in the sampling

[a] Hagen: “PM line loss correction without direct size measurement” 18th ETH conference on combustion generated nanoparticles, 2014.

system) are smaller than when the predicted modal diameters are relatively small, where there are significant changes in the penetration with size.

49) Further error propagation work needs to be performed to understand the amplified error impact on predicted engine exit concentration when either the mass and/or number instrument is below limit of quantification.

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Specifically for the Small helicopter engine:

51) For both ρ_{eff} equal to 1 and 0.55 g/cm^3, the predicted number concentration at the exit plane are of the order 1e8 P/cm^3, which is in the concentration range where coagulation could have an impact. If the loss functions are correct, the potential effects of this process need to be modelled to investigate the impact on DGN, facn and facm.

9. Appendices

9.1 EU/EASA System Setup compliance

AIR 6241 Entire System (4.1.1)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
4.1.1	PTS	Probe inlet to measurement instrument inlet	Sampling line configuration	Straight-through as possible	3PTS nvPM straight through splitter
			Sampling line length	≤ 35m	Yes
			Bends	• if necessary • radii ≥10 times the inside diameter of the line	Yes
			Fittings	• minimum number • stainless steel with a internal smooth bore	yes all unions bored out to avoid steps
			Step-shoulders	• no forward facing >15% of the ID (exclusive of 1PTS and 2PTS) • changes >15% of ID only at splitter flow path interface	steps are in isolation valve, 8% reduction & heated lines 3.2%
			Sample	Diluted within 8m of probe tip	Yes
			Residence times	theoretically calculated all	not EU reference issue
4.1.1.2	PTS	PTS thermal connections	Bulkhead union fittings	• kept to a minimum • thermally insulated (no cold spots)	All bulkheads insulated
			Union interface	• heat throughout the union interface • if not practically possible, as a minimum, isolate the sample line from the interface surface and heat up to within 5cm of the interface surface and insulate thermally throughout	no union interface
			bulkhead location	if required, only at interfaces between: 2PTS/3PTS, 3PTS/4PTS, 4PTS/5PTS and where practically required within 5PTS	2PTS/3PTS & 3PTS/4PTS
			Other PTS connection fittings	• heat across the connection where possible • If not practically possible, heat the sample line up to within 5 cm of the next heated section and insulate thermally in-between	N/A for CO_2 chiller required

AIR 6241 Collection Section (4.1.2)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
4.1.2.1	1PTS	Probe / Rake Hardware	Probe placement and configuration	• probe shall provide a representative emission sample • verified by means of detailed traverse measurement	Yes for in-production engine; For Lean staged engine carbon balance showed representativeness but no traverse performed
			Material	conductive, grounded, non-reacting material	Yes
			Number of Sampling Locations	≥12 locations	Yes
			Total orifice area (multi-orifices probe)	at least 80% of the dynamic head pressure drop through the probe assembly is taken at the orifices	Yes
			Multiple sampling orifices	of equal diameter	Yes
4.1.2.2	2PTS	Probe exit to splitter1 inlet	Sample Temperature	maintained ≥418K if active cooling is used	Yes
			Material	• Stainless Steel • carbon-loaded PTFE • or other non-reactive materials	Yes
			Inner Diameter (ID)	4 to 8.5mm	Yes
			Sampling line Temperature	• 433±15K (160 ± 15°C) • except for the distance required to cool the gas from the exhaust	Yes
4.1.2	1PTS & 2PTS	Probe inlet to splitter 1 inlet	Target residence time	≤ 3s through the collection section at low engine power conditions	Yes
			Length	≤ 8m	Yes

AIR 6241 Particle Transfer System (4.1.3)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
4.1.3.1	3PTS	Splitter 1 to Diluter 1 exit	Length	≤ 1m	86cm
4.1.3.1.1	3PTS	Splitter 1	Material	Stainless steel	Stainless Steel
			General geometry	• single triple-flow path • or two double-flow path (in series) • no forward facing shoulders on the inner wall • flow paths kept as short as-possible	Single triple
			Split angles	• as small as possible • ≤ 35°	split angles 30°
			Temperature	433±15K (160 ± 15°C)	160C set point
			Flow paths split	• PM sample flow • GTS flow for raw CO_2 measurement • excess sample flow	as explained
			Specific geometry	• inlet flow-path ID ≥ inlet line ID • Excess sample flow-path cross sectional area ≥ total inlet area of the probe tips • PM flow-path ID = Diluter1 inlet ID ≥ 7.59mm • GTS flow-path ID = 4 to 8.5 mm	ID equal
4.1.3.1.2	3PTS	Excess sample flow path	Pressure	P_1 maintained near 1 atm	yes
			Pressure control valve seal	• sufficient internal area • capable of operating at 10,000Pa (-100mbar) relative to ambient	isolating ball valve & control valve
4.1.3.1.3	3PTS	Diluter1	Location	after splitter1	yes
			Type	eductor-type to provide positive pressure and consistent sample flow to 4PTS	Dekati DI-1000
			Vent	open to ambient	yes, full bore
			Flow-path wall temperature	T_1 = 433±15K (160 ± 15°C) up to within 5cm of the venturi sample exit point	trace heated 160C
			Temperature	Diluter1 body = 333±15K (60 ± 15°C)	trace heated 60C
			Diluent pressure sensitivity	• set by a critical orifice at diluent inlet connector • orifice size as prescribed by the diluter manufacturer • pressure maintained to keep the flow critical through the orifice	as per manufacturers recommendation min 2bar inlet diluent pressure
			Inlet sample pressure sensitivity	• DF_1 controlled to within the range 8 to 13 (for a Diluter1 inlet pressure range of -5,500 to +5,500 Pa (-55 to +50 mbar) relative to ambient)	yes
			Penetration efficiency	• same methodology as utilised for VPR (6.1.3) with the required penetrations (Table 4.2)	Dekati DI-1000
			Diluent	• Nitrogen or air • HEPA filtered • contain <10ppm CO_2 • heated (to provide a diluted PM sample temperature of 333±15 K (60±15 °C) at the outlet of 3PTS)	yes as prescribed
			Isolation valve	• full bore (<15% shoulder step to sample line ID) • between splitter1 outlet and Diluter1 inlet • seals: dry and heat resistant to 448K (175°C)	yes
4.1.3.1.4	GTS	GTS flow-path	Sample line	ARP1256 specifications	8mm ID CLPTFE
			CO_2 analyser	ARP1256 specifications	measured dry, (not corrected to wet)

			Gas sample flow	• simultaneous with the PTS flow • at a flow rate to minimise the sample residence time in the Collection section	yes
4.1.3.2	4PTS	Diluter 1 exit to Cyclone inlet	Material	carbon-loaded, electrically grounded PTFE	ss to bulkhead then CL PTFE
			ID	7.59 to 8.15 mm	7.75 & 8mm
			Length	24.5±0.5 m	24.7m
			Sections	• maximum 3 • no bulkhead interfaces between the sections	1 continuous
			Sampling line temperature	333±15 K (60±15°C)	60C 3 point measurement
			Coiled bend	radii ≥ 0.5 m	no coil
			Flow rate	25±2 slpm	25sLPM
4.1.3.3	5PTS	Cyclone inlet - Splitter2 - instruments' inlet	Length	≤ 3m (not including flow path through cyclone?)	LII- 94cm APC- 45cm MSS- 127cm DMS- 45cm+500cm
4.1.3.3.1	5PTS	Cyclone	Material	Stainless steel	yes
			Temperature	333±15 K (60±15°C)	in oven 60C set point
			Cut-point	D_{50} = 1.0 ± 0.1 µm	BGI SCC 2.842 Cut-point 1.0 µm
			Sharpness	$(D_{16}/D_{84})^{0.5} \le 1.25$	BGI SCC 2.842 Sharpness 1.221
			Pressure-drop	Δp ≤ 2000 Pa (20 mbar)	BGI SCC 2.842 Δp 8 mbar
			inlet ID	difference with sample line outlet ID <15%	identical 7.75mm
4.1.3.3.2	5PTS	Splitter2	Material	Stainless steel	SS
			General geometry	• single triple-flow path • or two double-flow path (in series) • no forward facing shoulders on the inner wall • flow paths kept as short as possible	2 off compliant three way splitters as required for reference system
			Split angles	• as small as possible • ≤ 35°	30deg
			Flow paths split	• nvPMmi • volatile removal device (for nvPMni) • make-up flow	as required for reference additional mass
			Specific geometry	• inlet flow-path ID =cyclone outlet line ID ≥ 7.59mm • mass flow-path ID = inlet line ID of nvPMmi • number flow-path ID = inlet ID of VPR • inlet flow-path ID ≥ make-up flow-path ID If inlet dimensions for VPR and/or nvPMmi are optional, then relevant IDs = ID used in 4PTS	as prescribed
			Temperature	• T_3 = 333±15 K (60±15°C) • thermocouple placed in make-up flow-path at the outlet of Splitter2	in oven 60C
4.1.3.3.3	5PTS	Measurement System interface	Material	• Stainless steel • or carbon loaded, grounded PTFE	Stainless Steel
			Temperature	333±15 K (60±15°C)	Trace heated 60C
			ID	instruments inlet ID	7.75mm

AIR 6241 Measurement Section (4.1.4)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
4.1.4.1	Measurement Section	Make-up flow	Flow controller	air-equivalent volumetric range = 0 to 25 slpm	3 off 15sLPM
			Particle filter	upstream of the flow controller	cyclone and filter
			Pump and flow controller	capable of drawing up to 25 slpm from -10,000 Pa (-100 mbar) below ambient	yes
			Pressure	• P_3 to be measured • between Splitter2 outlet and particle filter	Measured by LII, MSS & APC
	Measurement Section	CO_2 analyser	Location	after flow controller	yes after needle valve
			Range	such that the anticipated concentrations shall be within 20 to 95% FS	yes 5000ppm
			Performance	ARP1256 specifications: • Zero Drift: less than 1% Full Scale in 1 hour • Span Drift: less than 1% Full Scale in 1 hour • Linearity: within ±1% Full Scale • Noise: less than ±1% Full Scale • Resolution: better than ±0.5% Full Scale • Precision: better than ±1% Full Scale • Response time: t_{90} < 10 seconds	yes

9.2 EU/EASA system Mass Instrument compliance

AIR 6241 Mass Instrument (5)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
5.1.1	Sampling Interface	Cyclone	cut-off	1 µm (D_{50})	as stated earlier
			location	before a flow splitter and the nvPMmi	yes in oven
			temperature	333±15 K (60±15°C)	oven 60C
		Sampling Line	Material	Stainless steel or grounded CLPTFE	Stainless Steel
			length	≤ 3m	LII- 94cm MSS- 127cm
			temperature	333±15 K (60±15°C)	trace heat 60C
		Splitter 2	outlet ID	ID = nvPMmi inlet ID	7.75mm
5.1.2.1	nvPMmi Specifications	performance	Range	1 mg/m^3	Artium LII-300 AVL MSS
			Resolution	1 µg/m^3	
			Repeatability	10 µg/m^3	
			Zero drift	10 µg/m^3/hr	
			Linearity	15 µg/m^3	
			LOD	3 µg/m^3	
			Rise time	2 sec	
			Sample rate	1 Hz	
			Accuracy	0.90 ≤ slope ≤ 1.10 • Slope of the linear regression between mass instrument and EC determined by NIOSH 5040	
5.1.2.2	nvPMmi Specifications	Performance uncertainty	linearity	instruments are linear	See NRC Calibration
			LOD	≤ 3µg/m^3	
			NIOSH5040	10%	
5.2	nvPMmi Specifications	Type Certification	Type Certificate	comparison of performance against specifications for each particular make and model of instrument	See NRC Calibration

AIR 6241 Mass Instrument Calibration (5.2)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
5.2.1 5.2.2 5.2.3	Mass Calibration system	Mass Calibration system set-up	Set-up	Figure 5.3 and Table 5.3	See NRC Calibration
			location		
			TOT analyser	• reports OC and EC contents in µg / cm^2 of filter area • detection limit on the order of 0.2 µg/cm^2	
			combustion source	diffusion flame combustion (e.g. Mini-CAST burner)	
			inlet source	proper inlet source gas	
			tubing	clean and dry polished stainless steel	
			Splitter	• 3 or 4 ways • same specification as in AIR6241 section 4	
			Cyclone	• 1 µm cut point stainless steel • same specification as in AIR6241 section 4	
			Diluter		
			Dilution stream	nitrogen	
			Quartz filter holder	• stainless steel • tapered inlet section with ≤ 12.5° half-angle • filter face velocity not exceeding 100 cm/s	
			Filter	• pre-fired quartz filter • 25 to 47 mm diameter	
			Semi-continuous EC/OC analyser	in situ filter EC/OC analyser	
			nvPMmi	AIR6241 compliant	
			Diagnostic particle analyser	optional	
			Mass flow controller	electronic	

9.3 EU/EASA system Number instrument compliance

AIR 6241 Number Instrument (6.0)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
6	Sampling Interface	Cyclone	cut-off	1 µm (D_{50})	as stated earlier
			location	before a flow splitter and the nvPMmi	yes in oven
			temperature	333±15 K (60±15°C)	oven 60C
		Sampling Line	Material	Stainless steel or grounded CLPTFE	Stainless Steel
			length	≤ 3m	APC- 45cm
			temperature	333±15 K (60±15°C)	trace heat 60C
		Splitter 2	outlet ID	ID = nvPMmi inlet ID	¼"-6mm union
6	nvPM number specification	Particle number system	Components	designed to minimize deposition of the particles	AVL APC
			All components	• electrically conductive materials that do not react with exhaust gas components • electrically grounded to prevent electrostatic effects	
			t_{90} total response time	≤10 s	
6.1.1	VPR specification	Sample Dilution Device	Dilution stages	one or more stages	2 stage
			Heated section	• 623 K (350°C) • residence time ≥ 0.25 s	yes (cal 300C)
		Diluted Sample	Concentration	below the upper threshold of the single particle count mode of the CPC	yes 10000 P/cm^3

			Temperature at CPC inlet	between 283 and 308 K (10 and 35°C)	yes
			Pressure to CPC inlet	+/- 15 kPa of ambient pressure	yes
		CS	if included		Yes
			if not used	place a heated dilution stage upstream which ○ outputs a sample at a temperature of ≥ 423 K (150°C) and ≤ 623 K (350°C) ○ dilutes by a factor ≥ 8	
		Line to CPC	Material	electrically conductive material	AVL APC
			ID	≥4 mm	4mm
			Residence time	≤ 0.8 s	AVL APC
		Penetration	solid (non-volatile) particle penetrations	• ≥30% at 15 nm • ≥55% at 30 nm • ≥65% at 50 nm • ≥70% at 100 nm • electrical mobility diameters	Yes see cal sheet
		Volatile Removal Efficiency	VRE	• >99.9% removal of tetracontane ($CH_3(CH_2)_{38}CH_3$) particles at: ○ 15 nm and inlet concentration ≥10,000 particles/cm^3 ○ 30 nm and inlet concentration ≥50,000 particles/cm^3 • electrical mobility diameters	Yes see calibration sheet
		Certification	Type Certificate	typical test results meet specifications for the family of instruments	AVL APC
			Initial Performance Check Certification	same as annual calibration certificate for each instrument	
6.1.4	DF2 determination equipment	DF stability	internal and logged DF stability control features	if option (2) for the DF_2 determination is chosen	AVL APC
		Diluent	• HEPA filtered gas (air or N_2) or • air with O_2 ≥10% (if CS used)		yes Air
		CO_2 analyser for option (1)	• concentrations as low as 10ppm • ARP1256 compliant • suitable range (FS: 30-70 ppm) • sample concentration in 20-95% of FS range • CO_2 <0.1ppm in diluent gas	if option (1) for the DF_2 determination is chosen	50ppm range
		CO_2 analyser for option (2)	• ARP compliant • suitable range	• if option (2) for the DF_2 determination is chosen • to monitor relative CO_2 changes for additional evaluation of dilution stability within 10% • no diluent CO_2 impurity limit required	yes
6.2	CPC Specifications	Method	Method	principle of condensing supersaturated butanol vapour on sub-micron size particles, which are then counted with an optical detector	yes
		Specifications	Working fluid	• reagent grade n-butanol • replacement frequency as specified by manufacturer	yes
			Flow	full flow operating conditions	yes
			Counting accuracy	10% from 2000 particles/cm^3 to upper threshold of single particle count mode	yes see cal cert

				against a traceable standard	
			Readability	≥ 0.1 particles/cm^3 at concentrations <100 particles/cm^3	yes
			Response	linear	can't be checked
			Mode	photometric mode not allowed	10000 P/cm^3
			Data reporting frequency	≥ 1.0 Hz	1Hz
			$t_{10\text{-}90}$ rise time	< 4s	TSI 3790/e
			Coincidence	coincidence correction function (≤10% correction)	"
			Counting efficiency curve	• ≥50% at 10 nm and ≥90% at 15 nm • electrical mobility diameters • determined with Emery Oil aerosol or another aerosol that provides an equivalent response	yes see cal cert
			Wick	replacement frequency as specified by manufacturer	serviced prior to test
			Pressure at CPC inlet	accuracy >2%	TSI 3790/e
		Type Certificate	Type Certificate	typical test results meet specifications for the family of instruments	?
		Initial Performance Check Certificate	Initial Performance Check Certificate	same as annual calibration certificate for each instrument	?

AIR 6241 Number Instrument Calibration (6.0)					
AIR 6241 Chapter	**Sampling Line section**	**Component**	**Criteria**	**Requirements**	**Compliance check**
6.1.3	VPR Calibration Equipment	Penetration	test particle	• soot generated by propane diffusion flame • downstream thermal pre-treatment device to deliver ≥ 5000 particles/ cm^3 for the four sizes	See calibration certificate
6.2.3	CPC Calibration Setup	Zero concentration	Filter	• HEPA or filter of equivalent performance • at the inlet of both instruments	See calibration certificate
		Calibration aerosol	Aerosol	• Emery oil or another aerosol that provides an equivalent response	

9.4 EU/EASA nvPM system Operability Compliance Spreadsheet

AIR 6241 Sampling system operation					
When	**AIR 6241 Chapter**	**Component**	**Operation Criteria**	**Requirements**	**Compliance check**
Pre-test	4.2.1.2	4 PTS	Inlet flow check	Optional: total 25±2 slpm while ensuring flow rates in each splitter2 branch are equivalent to those to be used during engine testing	Not performed, only optional
	4.2.1.1	1 PTS	Leak check	• control valve fully closed and probe tips blanked • using a vacuum pump and volume flow meter • ≤ 2.0 standard litres through the volume flow meter during a 5 min measurement	Yes
			Flow check	• ARP1256 methodology • 3 PTS isolated and spill valves fully closed	Yes, checked undiluted flow rate could meet 10s residence time
	4.1.3.1.2	3 PTS Excess sample flow path	Leak test	• control valve fully closed and probe tips blanked • using a vacuum pump and volume flow meter • ≤ 2.0 standard litres through the volume flow meter during a 5 min measurement	Yes,
	4.2.1.2.1	Transfer section	Leak check		Yes = cleanliness check below
			Flow audit	audit flow meters NMI traceably calibrated on a minimum annual basis	Yes, see cal certificates
			Pressure and Temperature sensor output calibration	minimum once a year with NMI traceable standards	Yes, instrument cal
			Device flow rate calibrations	as a minimum for: nvPMmi, VPR and make-up flow	Yes
	4.2.1.2.2		Cleanliness check	• flow clean, HEPA filtered diluent through Diluter1 with 3PTS isolation valve closed • ensure flow rates in each splitter2 branch are equivalent to those to be used during engine testing • measure mass concentrations for 3 minutes • average mass concentration ≤ 3 µg/m3 • measure number concentrations for 3 minutes at all DF2 settings that will be used during the engine measurements • CPC average value ≤ 0.5 particles/cm3 at each setting If the cleanliness test still fails after the recommended checks: either the dirty part of the	Yes, Mass passed, Number passed at all VPR dilution settings with limit at < 1 P/cm^3

				PTS section or measurement instrument shall be replaced	
	4.2.1.2.3	Cyclone	Cleanliness check	• empty and clean cyclone collection pot, if cleanliness test fails • or empty and clean cyclone collection pot on a minimum annual basis	Check did not fail, cleaned within 1 year
	4.2.1.2.4	Diluter1	Operability check	optional check • connect CO2 calibration gas (3 to 5%) to 1 PTS without over-pressurizing the probe tip inlet (calibration gas enters 1PTS at near ambient pressure) • PTS and GTS operated with the correct flow rates and at the correct temperatures • shut-off valve on the Excess Sample flow path closed • measure Diluter1 DF • if DF > 13 the GTS flow rate may be reduced depending on line compatibility requirements (4.1.3.1.4)	Not performed, only optional
	4.1.4.1	CO_2 analyser	Audit calibration check	• ARP1256 procedures • zero gas specification = Diluter1 diluent (≠ ARP1256) • certified span gas concentration = 90 to 100% of analyser FS	Yes, performed
During test	4.1.3.2	Transfer section	DF1 control	measure P1	Yes, differential pressure control
	4.1.3.2	4 PTS	Flow monitoring	monitored online via the three calibrated flow measurements downstream of splitter2 (nvPMmi, Volatile removal device and make-up flow)	Yes
	4.2.1.2.1	4 PTS	Sample flow rate	25±2 slpm validated by summation of the inlet flow rates: nvPMmi, Volatile removal device and make-up flow	25 slpm validated via 2 mfc and AVL/MSS/DMS instrument measurements
	4.2.2.1	Collection section	Backpurging	• close 3PTS isolation valve during engine start-up and shutdown • back purge using ambient air or compressed inert gas	Yes, using compressed air
	4.2.2.2	All PTS	Conditioning	If any part of the PTS is new, previously cleaned or not having been previously used for aircraft combustor exhaust sampling, sample aircraft engine exhaust for a minimum of 30 minutes at any engine power condition prior to obtaining nvPM measurements	Yes
	4.2.2.4		Ambient particle check	• report ambient air particle mass and number concentration representative of engine air inlet • measure at least 5 minutes after engine start-up and just prior engine shutdown • measure mass concentration for 3 minutes • measure number concentration for 3 minutes at the lowest DF2 used during engine testing ; the CPC average dilution-corrected value ≥ 10 times the value measured for the cleanliness check ; if this check fails, verify system operation and repeat measurement •record the average of the two readings each for mass and number	Yes
	4.2.2.5		nvPMni ambient pressure	Ensure that the diluted sample to the CPC is within +/- 15 kPa of ambient pressure	Yes as per APC design
	4.1.4.1	CO_2 analyser	Diluted CO_2	• to measure [CO2_dil1] • no need to dry the diluted sample as long as the diluted sample dewpoint does not increase above	Diluted sample not dried, measured wet

				the semi-dried raw gas temperature • If this dewpoint limit is exceeded, the sample shall be dried and corrected to CO2 wet	

AIR 6241 Mass Measurement Operation					
AIR 6241 Chapter	**AIR 6241 Chapter**	**Component**	**Operation Criteria**	**Requirements**	**Compliance check**
Calibration	5.2.3	nvPMmi	Type certificate	• target soot concentrations in AIR6241 Table 5.4 • actual concentration within 20% of target concentration	Yes, as per NRC calibration
			Initial performance check	• target soot concentrations in AIR6241 Table 5.4 • actual concentration within 20% of target concentration	
			Annual calibration	• target soot concentrations in AIR6241 Table 5.4 • actual concentration within 20% of target concentration	
	5.2.1	nvPMmi	Calibration method	• compared to reference method by a suitable testing laboratory • reference method: NIOSH 5040 protocol	Yes, as per NRC calibration
			nvPM source	diffusion flame EC > 0.8	
			EC determination	TOT Carbon Analyser	
			Analytical procedures	ISO 9169:2006 and NIOSH 5040	
	5.2.3	nvPMmi	Sample analysis	at least one punch from each filter	Yes, as per NRC calibration
	5.2.5	nvPMmi	Data reduction	least squares fit through zero	Yes, as per NRC calibration
Operability	5.3	nvPM mass data	Data recorded	• 1 Hz data converted to STP • 30 s averages	Yes
			CO_2 concentration (after Diluter 1)	• recorded at same rate as nvPM mass • recorded over same time period as nvPM mass	Yes
			Fuel composition	Carbon analysis	Yes
			nvPM mass Emission Index	calculated from mass concentrations, fuel composition and CO_2 concentration (after Diluter 1)	Yes

	AIR 6241 Number measurement operation				
	AIR 6241 Chapter	**Component**	**Operation criteria**	**Requirements**	**Compliance check**
Operability	6.1.1	VPR	If CS not used	Control heated stages to constant nominal operating temperatures, within the range ≥ 423 K (150°C) and ≤ 623 K (350°C), to a tolerance of ±10 K (±10 °C).	Not applicable, CS used
Calibration	6.1.2	VPR	Periodic calibration	• within a 6-month period prior to the emissions test • 12 month calibration or validation interval (if VPR incorporates temperature monitoring alarms)	Yes, 5 months before emissions test
			Calibration after major maintenance	Calibration of VPR across full range of dilution settings, at VPR fixed nominal operating temperatures	Not perfomed, no major maintenance

	6.1.3	VPR	DF2	• measured or determined for each VPR setting • with trace gases or flow measurement	Yes as per AVL calibration
			Penetration	• calculated for each VPR DF setting • specifically for 15, 30, 50 and 100 nm • measured upstream and downstream of VPR components with CPC • CPC with ≥ 90% counting efficiency for 15nm particles	Yes as per AVL calibration.
			Volatile Removal Efficiency	• >99.9% removal of tetracontane (CH3(CH2)38CH3) particles at: o 15 nm and inlet concentration ≥10,000 particles/cm3 o 30 nm and inlet concentration ≥50,000 particles/cm3 • VPR operated at minimum dilution setting • operating temperature recommended by manufacturer • determined with CPC With D90 at 15nm	Yes as per AVL calibration
Operability	6.1.4	VPR dilution	DF2 determination	two options: (1) real time CO2 measurement at CPC inlet (2) DF2 value given by VPR dilution calibration • option (2): o DF2 check pre and post engine test o checked DF2 variability <10% compared to DF2 given by VPR dilution calibration (or recalibration of VPR dilution)	(2) only
	6.1.5	VPR pre-test checks	Operating temperature	Correct operating temperature reached	Yes
			DF2 check	• 100% CO2 sample (or other practical CO2 concentration) at VPR inlet with same inlet flow rate, P and T, as used during engine test • CO2 pulled from setup which does not under pressure or overpressure the VPR inlet • CO2 concentration measured at VPR outlet for each DF set point used during engine measurement	Yes, measured DF used for PM calculations
			Other checks	As recommended by manufacturer	Yes, as specified by AVL
	6.2.1	STP correction	Pressure	Measured at CPC inlet	As reported by AVL APC
			Temperature	Measured at CPC inlet	
Calibration	6.2.2	CPC	Periodic calibration	• within a 6-month period prior to the emissions test • 12 month calibration or validation interval (if CPC incorporates temperature and flow rate monitoring alarms) • to be performed after major maintenance	Yes, 11 months before Lean burn staged engine, 1.5 months before in-production engine
	6.2.3	CPC	Calibration method	traceable to a standard calibration method (ISO 27891): • compare CPC response with that of a calibrated aerosol electrometer o electrostatically classified calibration particles sampled simultaneously	Yes, as per TSI cal certificate
			Linearity concentration set points	• ≥ 6 • spaced uniformly across measurement range • include a nominal zero concentration point	
			Linearity measurement	within ±10 % of the standard concentrations	
			Linear regression	• calculate gradient from a linear regression of the two data sets • k = reciprocal of the gradient	

				• apply k to CPC under calibration • R2 ≥ 0.97 for the two data sets • fit forced through zero on both instruments	
			Counting efficiency	• counting efficiency of ≥50% at 10 nm and ≥90% at 15 nm • with particles of 10 nm and 15 nm electrical mobility diameter	
			Calibration type of aerosol	• Emery oil or • another aerosol that provides an equivalent response	
Operability	6.2.4	CPC pre-test checks	Saturator	correct operating temperature reached	Yes, as reported by AVL APC
			Condenser	correct operating temperature reached	
			Flow audit	verify proper operation with flow audit (pressure or flow measurements)	
			Working fluid quantity	at the level required by the manufacturer	
	6.2.5	CPC pre-test checks	Quality Control check	• conducted according to the manufacturer's recommendations • include flow rate	Yes, as reported by AVL APC
	6.3	nvPM number data	Data recorded	• ≥ 1Hz • ≥ 30s interval • once the engine is stabilized	Yes, data as reported by AVL APC
			STP reporting	If the instrument output concentration is not at the STP condition, follow the manufacturer's recommendation to correct the measured particle concentration to the STP condition	

9.5 Calibration Certificates

9.5.1 AVL APC calibrations Nov 2013 & Oct 2014

AVL

AVL 489 Particle Counter Aviation Calibration Certificate

Date:	28-Nov-2013	
Device:	GH0672	382
	Chopper Diluter	460

Makro	XF0339	V1.27_b3

Used Instruments	Type	Serial No.
DMA	TSI 3080N	71207121
Master CPC	TSI 3772	3772113102
Mass Flow Meter	RedY GCR-B5SA-BA25	137315
Calibration aerosol: APG combustion soot		

Measured Inlet Flows of Instruments

Device	Vol. Flow	Normalization Cond.
APC Chopper Dil. low	4563 ml/min	25°C; 1013.25mbar
Master CPC	1014 ml/min	ambient conditons

Zero Concentration with HEPA-Filter

APC	0.26 #/cm³	at pcrf=10*10=100
Master CPC	0.001 #/cm³	

Nr	values set				Flows	Measured Penetrations			
	Diluter 1 low/high	Diluter 1	Diluter 2	set pcrf	Dilution Factor	100nm (>70%)	50nm (>65%)	30nm (>55%)	15nm (>30%)
1	low	10	10	**100**	**66**	72.1%	67.6%	60.4%	39.3%
2	low	25	10	**250**	**169**	73.8%	70.4%	61.3%	40.9%
3	low	50	10	**500**	**340**	73.6%	70.5%	61.4%	39.5%
4	low	100	10	**1000**	**687**	73.6%	70.5%	62.9%	38.0%
5	low	150	10	**1500**	**1011**	73.9%	69.5%	60.5%	38.0%
6	low	200	10	**2000**	**1325**	72.7%	68.1%	59.5%	37.5%
7	low	200	15	**3000**	**2038**	74.2%	68.6%	62.4%	35.4%

Volatile Particle Removal Efficiency for Tetracontane 15nm:	**99.95%**
Volatile Particle Removal Efficiency for Tetracontane 30nm:	**99.95%**

AVL List GmbH does hereby certify that the above described instrument conforms to the original manufacturer's specifications and has been calibrated using standards whose accuracies are traceable to national standards or have been derived from accepted values of natural physical constants or have been derived by the ration type of self calibration techniques. This report may not be reproduced, except in full, unless permission for the publication of an approved abstract is obtained in writing from the calibration organization issuing this report.

Signature

(CELIK Caglayan)

Page 1 of 2

Nr	Flows Dilution Factor	Measured particles dilution 100 nm	50 nm	30 nm	15 nm
1	**66**	92	98	110	168
2	**169**	230	241	276	414
3	**340**	462	482	553	860
4	**687**	934	975	1093	1810
5	**1011**	1368	1454	1672	2662
6	**1325**	1824	1946	2225	3534
7	**2038**	2745	2972	3265	5753

Pressures during calibration

Sample Rel. Pressure	-48 mbar
Diluted. Rel. Pressure	28 mbar
Absolute Pressure	986 mbar

Demand temperatures during calibration

Catalytic Stripper Temperature	350 °C
Diluter 1 Temperature	150 °C

Calibration values set in firmware

Directly measured values for the seven fixed PCRF settings

PCRF	calib. value
100	1.16
250	1.13
500	1.13
1000	1.12
1500	1.14
2000	1.16
3000	1.13

Interpolated values for variable PCRF settings*

Diluter 1 low	
Diluter 2	**calib. value**
10	1.16
15	1.00
20	1.00

* These values are calculated by averaging the values measured at the highest and the lowest Diluter 1 setting for each Diluter 2 setting.

AVL 489 Particle Counter Aviation Calibration Certificate

*Only calibrated at Stages 1-5. One of those stages MUST be used for AIR6241 compliant measurements.

Date: 10-Oct-2014	
Device: GH0965	382
Chopper Diluter	460

Makro	XF0339	V1.27

Used Instruments	Type	Serial No.
DMA	TSI 3080N	71207121
Master CPC	TSI 3772	3772121004
Mass Flow Meter	RedY GCR-B5SA-BA25	137315
Calibration aerosol: APG combustion soot		

Measured Inlet Flows of Instruments		
Device	Vol. Flow	Normalization Cond.
APC Chopper Dil. low	4573 ml/min	25°C; 1013.25mbar
Master CPC	998 ml/min	ambient conditons

Zero Concentration with HEPA-Filter		
APC	0.08 #/cm³	at pcrf=10*10=100
Master CPC	0.006 #/cm³	

	values set				Flows	Measured Penetrations			
Nr	Diluter 1 low/high	Diluter 1	Diluter 2	set pcrf	Dilution Factor	100nm (>70%)	50nm (>65%)	30nm (>55%)	15nm (>30%)
1	low	10	10	100	65	72.3%	66.9%	58.0%	35.7%
2	low	25	10	250	171	75.5%	71.3%	60.9%	37.9%
3	low	50	10	500	340	74.9%	70.5%	60.5%	37.6%
4	low	100	10	1000	674	73.7%	70.2%	60.1%	36.4%
5	low	150	10	1500	1012	75.0%	71.3%	58.5%	34.9%

Volatile Particle Removal Efficiency for Tetracontane 15nm:	99.98%
Volatile Particle Removal Efficiency for Tetracontane 30nm:	100.00%

AVL List GmbH does hereby certify that the above described instrument conforms to the original manufacturer's specifications and has been calibrated using standards whose accuracies are traceable to national standards or have been derived from accepted values of natural physical constants or have been derived by the ration type of self calibration techniques. This report may not be reproduced, except in full, unless permission for the publication of an approved abstract is obtained in writing from the calibration organization issuing this report.

Signature

(CELIK Caglayan)

Nr	Flows Dilution Factor	Measured particles dilution			
		100 nm	50 nm	30 nm	15 nm
1	**65**	90	98	113	183
2	**171**	227	240	281	452
3	**340**	454	482	562	905
4	**674**	916	961	1124	1855
5	**1012**	1348	1419	1729	2899

Pressures during calibration

Sample Rel. Pressure	-49 mbar
Diluted. Rel. Pressure	19 mbar
Absolute Pressure	972 mbar

Demand temperatures during calibration

Catalytic Stripper Temperature	350 °C
Diluter 1 Temperature	150 °C

Calibration values set in firmware

Directly measured values for the seven fixed PCRF settings

PCRF	calib. value
100	1.18
250	1.12
500	1.13
1000	1.14
1500	1.14
2000	1.00
3000	1.00

Interpolated values for variable PCRF settings*

Diluter 1 low	
Diluter 2	**calib. value**
10	1.00
15	1.00
20	1.00

* These values are calculated by averaging the values measured at the highest and the lowest Diluter 1 setting for each Diluter 2 setting.

9.5.2 TSI CPC Service and Calibrations June 2014 & Oct 2014

TSI GmbH
Neuköllner Straße 4
52068 Aachen
Germany

Page 1 of 1

SERVICE REPORT

RMA Number: 800335678

Customer: 517775

AVL List GmbH
HANS-LIST-PLATZ 1
8020 GRAZ
ÖSTERREICH

Date Completed: 18 Jun 2014

Shipping Address: 30836

CARDIFF UNIV
SCHOOL OF ENGINEERING
5 THE PARADE
CARDIFF, SOUTH GLAMORGAN
South Glamorgan
CF24 3AA
UNITED KINGDOM

Customer PO: 4203301

Description: Maintenance and Calibrati on 3790-AVL

Model: PAID0238

Serial Number: 3790132002

Return Reason:
CALIBRATION AND SERVICE TSI CPC3792EDEVICE ALREADY AT TSI UKDEVICE WAS S ENT DIRECTLY FROM CUSTOMER
TO UKMORRIS, GARETHCALIBRATION AND SERVICE AT TSI UK

Technician:
Daniel Hatton

Technician's Findings:
Instrument received for calibration.

Technician's Actions:
Carried out service: Replaced tubing as needed, cleaned flow orifice and nozzle. Replaced wick and cleaned wick mounting base and aerosol inlet tube. Test of cooling device for condenser over ten minutes to make sure temperature can be lowered and maintained. Checked Condenser and Saturator display temperature values are correct with Calibrated temperature probe. Leak check carried out. Verify liquid fill function and liquid level sensor calibration. Verify Flow. Calibrated at D50 (10nm) and D90 (15nm), Linearity test (41nm). 12 hour zero test carried out. All Calibration tests were passed and found to be within instrument specifications. The instrument has been cleaned and a function check carried out.

Thank you for the opportunity to service your instrument.

CPC MODEL 3790E CERTIFICATE OF CALIBRATION

3790132002	Serial Number	Test Aerosol: Emery Oil
18 June 2014	Date	

Inlet Flow

		Units	Low Limit	High Limit
0.99	Measured Flow (Volumetric)	L/min	0.95	1.05
0.916	Calculated Flow (Standard)	SL/min	-	-

Standard Conditions: 0° C, 101.3 kPa

Temperature and Pressure

		Units	Low Limit	High Limit
20.94	Room Temperature	°C	-	-
46%	Room Relative Humidity	-	-	-
100.9	Room Barometric Pressure	kPa	-	-
39	Saturator Temperature	°C	38	40
22	Condenser Temperature	°C	20	24
40	Optics Temperature	°C	39.8	40.2
29.5	Cabinet Temperature	°C	20	35
70.9	Pressure Drop Across Orifice	kPa	70	88
0.7	Pressure Drop Across Nozzle	kPa	0.2	1

Laser Check

		Units	Low Limit	High Limit
17	Laser Power (Measured)	mW	14	20

Optics

		Units	Low Limit	High Limit
44	Laser Current Reading	mA	12	-
2	Minimum Pulse Height	V	1	3.65
600	Minimum Pulse Width	ns	230	950
3	Maximum Pulse Height	V	2	3.65
700	Maximum Pulse Width	ns	230	950

Zero Count Test

		Units	Low Limit	High Limit
0	Concentration Average Over 12 Hours	p/cc	0	0.001

Lower Detection & Concentration Linearity Test Results

		Units	Low Limit	High Limit
51.0%	10 nm Particle Counting Efficiency	-	50%	-
93.7%	15 nm Particle Counting Efficiency	-	90%	-
96.8%	Linearity Test: Slope (up to 10,000 p/cc)	-	90%	110%
0.9992	Linearity of Regression (R^2)	-	0.97	-

Final Voltage Measurements

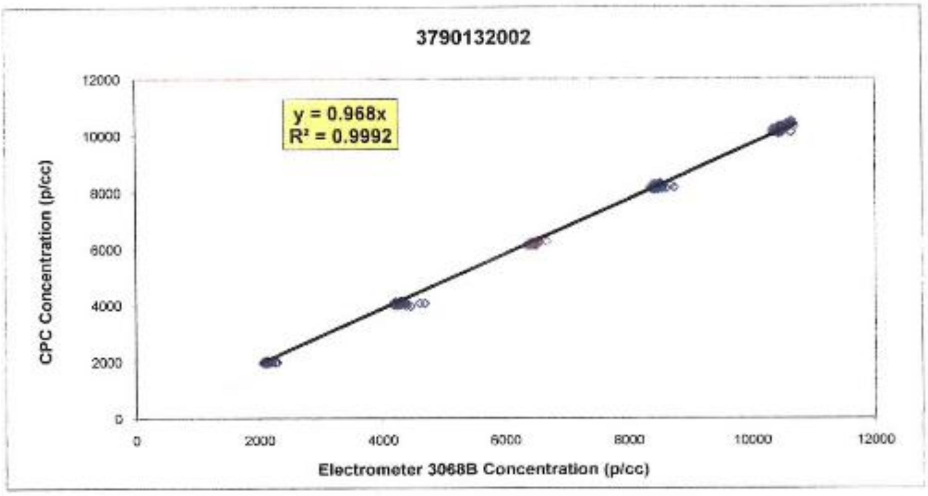
Pass	Analog Input and Output Voltages

Linearity Response: CPC vs. Electrometer 3068B

Nominal Conc.	UUT	Electrometer	%Difference	Units	Low Limit	High Limit
2000 p/cc	1999.44	2117.99	-5.60%	% Diff.	-10%	10%
4000 p/cc	4056.00	4275.99	-5.14%	% Diff.	-10%	10%
6000 p/cc	6195.51	6457.41	-4.06%	% Diff.	-10%	10%
8000 p/cc	8200.56	8468.02	-3.16%	% Diff.	-10%	10%
10000 p/cc	10247.25	10507.69	-2.48%	% Diff.	-10%	10%

Particle Size Used in Linearity Test: 55 nm

LINEARITY RESPONSE



TSI Incorporated does hereby certify that the above described instrument conforms to the original manufacturer's specifications (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to the National Institute of Standards and Technology within the limitations of NIST's calibration services or have been derived from accepted values of natural physical constants or have been derived by the ratio type of self calibration techniques. The calibration ratio for this instrument is at least 1:1. TSI's calibration system meets ISO-9001:2000 and complies with ISO 10012:2003, Quality Assurance Requirements for Measuring Equipment. This report may not be reproduced, except in full, unless permission for the publication of an approved abstract is obtained in writing from the calibration organization issuing this report

Measurement Variable	System ID Number	Date Last Calibrated	Calibration Date Due
High Voltage Divider	UK 20001948	15 March 2012	15 March 2017
Voltage Measurement	UK 82100066	11 July 2013	11 July 2014
Electrometer	UK 71231036	31 October 2013	31 October 2014
Aerosol Flow	UK 1207095-S	08 August 2013	08 August 2014
Classifier Flow	E006118	10 January 2014	10 January 2015
Temperature Measurement	E006157	22 November 2013	22 November 2014
Barometric Pressure Gage	E006013	17 March 2014	17 March 2015
Temperature/Humidity Gage	E006014	17 March 2014	17 March 2015

Daniel Hatton
Calibrated By

18 June 2014
Calibration Date

TSI - 3790 Zero Count Test

Test Instrument:	Model 3790 Ver 2.31 S/N 379013200	**Burst Counts > 20:**	PASSED Limit: 4 Actual: 0
Time of Test:	06-17-2014 16:31:03	**OverAll Conc.:**	PASSED Limit: 0.001 Actual: 0.000
Technician :	DH	**Max. Count:**	PASSED Limit: 200 Actual: 7

Measurement Interval : 12:00:01

Sample Time :: Particle Count

06/17/14 16:41 = 0	06/17/14 22:31 = 0	06/18/14 04:21 = 0
06/17/14 16:51 = 0	06/17/14 22:41 = 0	06/18/14 04:31 = 0
06/17/14 17:01 = 0	06/17/14 22:51 = 0	
06/17/14 17:11 = 0	06/17/14 23:01 = 0	
06/17/14 17:21 = 0	06/17/14 23:11 = 0	
06/17/14 17:31 = 0	06/17/14 23:21 = 0	
06/17/14 17:41 = 0	06/17/14 23:31 = 0	
06/17/14 17:51 = 2	06/17/14 23:41 = 0	
06/17/14 18:01 = 0	06/17/14 23:51 = 0	
06/17/14 18:11 = 0	06/18/14 00:01 = 0	
06/17/14 18:21 = 0	06/18/14 00:11 = 0	
06/17/14 18:31 = 0	06/18/14 00:21 = 0	
06/17/14 18:41 = 0	06/18/14 00:31 = 0	
06/17/14 18:51 = 0	06/18/14 00:41 = 0	
06/17/14 19:01 = 0	06/18/14 00:51 = 0	
06/17/14 19:11 = 0	06/18/14 01:01 = 0	
06/17/14 19:21 = 0	06/18/14 01:11 = 0	
06/17/14 19:31 = 0	06/18/14 01:21 = 0	
06/17/14 19:41 = 0	06/18/14 01:31 = 0	
06/17/14 19:51 = 0	06/18/14 01:41 = 1	
06/17/14 20:01 = 0	06/18/14 01:51 = 0	
06/17/14 20:11 = 7	06/18/14 02:01 = 0	
06/17/14 20:21 = 0	06/18/14 02:11 = 0	
06/17/14 20:31 = 0	06/18/14 02:21 = 0	
06/17/14 20:41 = 0	06/18/14 02:31 = 0	
06/17/14 20:51 = 0	06/18/14 02:41 = 0	
06/17/14 21:01 = 0	06/18/14 02:51 = 0	
06/17/14 21:11 = 0	06/18/14 03:01 = 0	
06/17/14 21:21 = 0	06/18/14 03:11 = 0	
06/17/14 21:31 = 0	06/18/14 03:21 = 0	
06/17/14 21:41 = 0	06/18/14 03:31 = 0	
06/17/14 21:51 = 0	06/18/14 03:41 = 0	
06/17/14 22:01 = 0	06/18/14 03:51 = 1	
06/17/14 22:11 = 0	06/18/14 04:01 = 0	
06/17/14 22:21 = 0	06/18/14 04:11 = 0	

SAMPLE III

TSI GmbH
Neuköllner Straße 4
52068 Aachen
Germany

SERVICE REPORT

RMA Number: 800335678

Date Completed: 18 Jun 2014

Customer: 517775

AVL List GmbH
HANS-LIST-PLATZ 1
8020 GRAZ
ÖSTERREICH

Shipping Address: 30836

CARDIFF UNIV
SCHOOL OF ENGINEERING
5 THE PARADE
CARDIFF, SOUTH GLAMORGAN
South Glamorgan
CF24 3AA
UNITED KINGDOM

Customer PO: 4203301

Description: Maintenance and Calibrati on 3790-AVL

Model: PAID0238

Serial Number: 3790132002

Return Reason:
CALIBRATION AND SERVICE TSI CPC3792EDEVICE ALREADY AT TSI UKDEVICE WAS S ENT DIRECTLY FROM CUSTOMER
TO UKMORRIS, GARETHCALIBRATION AND SERVICE AT TSI UK

Technician:
Daniel Hatton

Technician's Findings:
Instrument received for calibration.

Technician's Actions:
Carried out service: Replaced tubing as needed, cleaned flow orifice and nozzle. Replaced wick and cleaned wick mounting base and aerosol inlet tube. Test of cooling device for condenser over ten minutes to make sure temperature can be lowered and maintained. Checked Condenser and Saturator display temperature values are correct with Calibrated temperature probe. Leak check carried out. Verify liquid fill function and liquid level sensor calibration. Verify Flow. Calibrated at D50 (10nm) and D90 (15nm), Linearity test (41nm). 12 hour zero test carried out. All Calibration tests were passed and found to be within instrument specifications. The instrument has been cleaned and a function check carried out.

Thank you for the opportunity to service your instrument.

CPC MODEL 3790E CERTIFICATE OF CALIBRATION

3790132002	Serial Number
18 June 2014	Date

Test Aerosol: Emery Oil

Inlet Flow

Value	Parameter	Units	Low Limit	High Limit
0.99	Measured Flow (Volumetric)	L/min	0.95	1.05
0.916	Calculated Flow (Standard)	SL/min	-	-

Standard Conditions: 0° C, 101.3 kPa

Temperature and Pressure

Value	Parameter	Units	Low Limit	High Limit
20.94	Room Temperature	°C	-	-
46%	Room Relative Humidity	-	-	-
100.9	Room Barometric Pressure	kPa	-	-
39	Saturator Temperature	°C	38	40
22	Condenser Temperature	°C	20	24
40	Optics Temperature	°C	39.8	40.2
29.5	Cabinet Temperature	°C	20	35
70.9	Pressure Drop Across Orifice	kPa	70	88
0.7	Pressure Drop Across Nozzle	kPa	0.2	1

Laser Check

Value	Parameter	Units	Low Limit	High Limit
17	Laser Power (Measured)	mW	14	20

Optics

Value	Parameter	Units	Low Limit	High Limit
44	Laser Current Reading	mA	12	-
2	Minimum Pulse Height	V	1	3.65
600	Minimum Pulse Width	ns	230	950
3	Maximum Pulse Height	V	2	3.65
700	Maximum Pulse Width	ns	230	950

Zero Count Test

Value	Parameter	Units	Low Limit	High Limit
0	Concentration Average Over 12 Hours	p/cc	0	0.001

Lower Detection & Concentration Linearity Test Results

Value	Parameter	Units	Low Limit	High Limit
51.0%	10 nm Particle Counting Efficiency	-	50%	-
93.7%	15 nm Particle Counting Efficiency	-	90%	-
96.8%	Linearity Test: Slope (up to 10,000 p/cc)	-	90%	110%
0.9992	Linearity of Regression (R^2)	-	0.97	-

Final Voltage Measurements

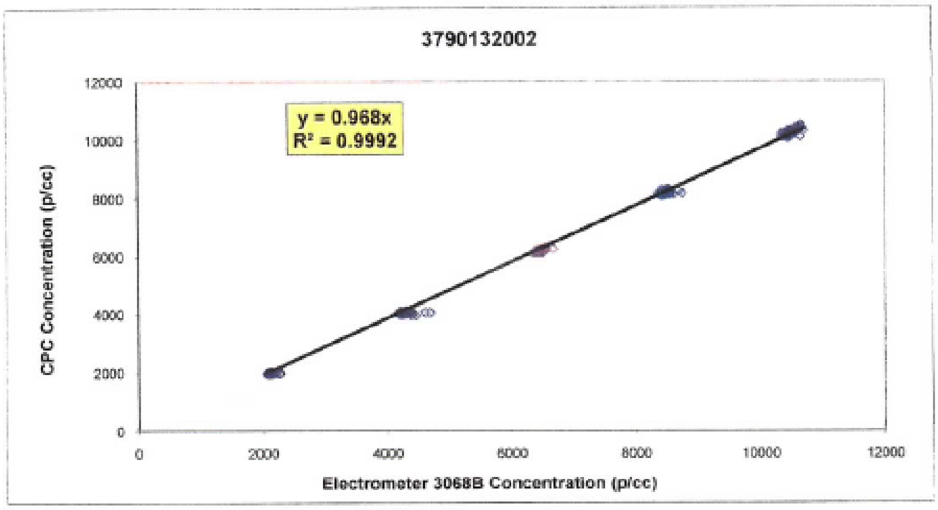
Value	Parameter
Pass	Analog Input and Output Voltages

Linearity Response: CPC vs. Electrometer 3068B

Nominal Conc.	UUT	Electrometer	%Difference	Units	Low Limit	High Limit
2000 p/cc	1999.44	2117.99	-5.60%	% Diff.	-10%	10%
4000 p/cc	4056.00	4275.99	-5.14%	% Diff.	-10%	10%
6000 p/cc	6195.51	6457.41	-4.06%	% Diff.	-10%	10%
8000 p/cc	8200.56	8468.02	-3.16%	% Diff.	-10%	10%
10000 p/cc	10247.25	10507.69	-2.48%	% Diff.	-10%	10%

Particle Size Used in Linearity Test: 55 nm

LINEARITY RESPONSE



TSI Incorporated does hereby certify that the above described instrument conforms to the original manufacturer's specifications (not applicable to As Found data) and has been calibrated using standards whose accuracies are traceable to the National Institute of Standards and Technology within the limitations of NIST's calibration services or have been derived from accepted values of natural physical constants or have been derived by the ratio type of self calibration techniques. The calibration ratio for this instrument is at least 1:1. TSI's calibration system meets ISO-9001:2000 and complies with ISO 10012:2003, Quality Assurance Requirements for Measuring Equipment. This report may not be reproduced, except in full, unless permission for the publication of an approved abstract is obtained in writing from the calibration organization issuing this report

Measurement Variable	System ID Number	Date Last Calibrated	Calibration Date Due
High Voltage Divider	UK 20001948	15 March 2012	15 March 2017
Voltage Measurement	UK 82100066	11 July 2013	11 July 2014
Electrometer	UK 71231036	31 October 2013	31 October 2014
Aerosol Flow	UK 1207095-S	08 August 2013	08 August 2014
Classifier Flow	E006118	10 January 2014	10 January 2015
Temperature Measurement	E006157	22 November 2013	22 November 2014
Barometric Pressure Gage	E006013	17 March 2014	17 March 2015
Temperature/Humidity Gage	E006014	17 March 2014	17 March 2015

Daniel Hatton	18 June 2014
Calibrated By	Calibration Date

TSI - 3790 Zero Count Test

Test Instrument:	Model 3790 Ver 2.31 S/N 379013200	**Burst Counts > 20:**	PASSED Limit: 4 Actual: 0
Time of Test:	06-17-2014 16:31:03	**OverAll Conc.:**	PASSED Limit: 0.001 Actual: 0.00
Technician :	DH	**Max. Count:**	PASSED Limit: 200 Actual: 7

Measurement Interval : 12:00:01

Sample Time :: Particle Count

06/17/14 16:41 = 0	06/17/14 22:31 = 0	06/18/14 04:21 = 0
06/17/14 16:51 = 0	06/17/14 22:41 = 0	06/18/14 04:31 = 0
06/17/14 17:01 = 0	06/17/14 22:51 = 0	
06/17/14 17:11 = 0	06/17/14 23:01 = 0	
06/17/14 17:21 = 0	06/17/14 23:11 = 0	
06/17/14 17:31 = 0	06/17/14 23:21 = 0	
06/17/14 17:41 = 0	06/17/14 23:31 = 0	
06/17/14 17:51 = 2	06/17/14 23:41 = 0	
06/17/14 18:01 = 0	06/17/14 23:51 = 0	
06/17/14 18:11 = 0	06/18/14 00:01 = 0	
06/17/14 18:21 = 0	06/18/14 00:11 = 0	
06/17/14 18:31 = 0	06/18/14 00:21 = 0	
06/17/14 18:41 = 0	06/18/14 00:31 = 0	
06/17/14 18:51 = 0	06/18/14 00:41 = 0	
06/17/14 19:01 = 0	06/18/14 00:51 = 0	
06/17/14 19:11 = 0	06/18/14 01:01 = 0	
06/17/14 19:21 = 0	06/18/14 01:11 = 0	
06/17/14 19:31 = 0	06/18/14 01:21 = 0	
06/17/14 19:41 = 0	06/18/14 01:31 = 0	
06/17/14 19:51 = 0	06/18/14 01:41 = 1	
06/17/14 20:01 = 0	06/18/14 01:51 = 0	
06/17/14 20:11 = 7	06/18/14 02:01 = 0	
06/17/14 20:21 = 0	06/18/14 02:11 = 0	
06/17/14 20:31 = 0	06/18/14 02:21 = 0	
06/17/14 20:41 = 0	06/18/14 02:31 = 0	
06/17/14 20:51 = 0	06/18/14 02:41 = 0	
06/17/14 21:01 = 0	06/18/14 02:51 = 0	
06/17/14 21:11 = 0	06/18/14 03:01 = 0	
06/17/14 21:21 = 0	06/18/14 03:11 = 0	
06/17/14 21:31 = 0	06/18/14 03:21 = 0	
06/17/14 21:41 = 0	06/18/14 03:31 = 0	
06/17/14 21:51 = 0	06/18/14 03:41 = 0	
06/17/14 22:01 = 0	06/18/14 03:51 = 1	
06/17/14 22:11 = 0	06/18/14 04:01 = 0	
06/17/14 22:21 = 0	06/18/14 04:11 = 0	

Page 1 of 1

9.5.3 Mass flow controller calibration certificates

Bronkhorst®
UK

CALIBRATION CERTIFICATE

FLUID NO. 1 OF 1
CERTIFICATE NO. BHTUK/095180

Calibration by comparison
Calibration date: 28 Oct 2014

We hereby certify that the instrument mentioned below has been calibrated in accordance with the stated values and conditions. The calibration standards used are traceable to national standards of the Dutch Metrology Institute VSL.

Calibrated instrument

Type	Flow controller (D)
Serial number	M13204236A
Model number	F-201CV-10K-ABD-22-V
Rated accuracy*	±(0.5%Rd + 0.1%FS)

Calibration standard

Type	Rotor meter
Serial number	M1207508C
Certificate no.	NMi/G13S2950
Uncertainty	±0.3% Rd

Customer conditions

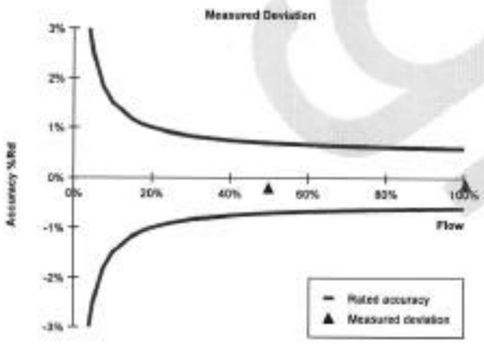
Fluid	**AiR**
Flow	**12.50 ls/min**
Pressure	**900.0 mbar (a)**
Temperature	**5.0..40.0 °C**

Calibration conditions

Fluid	AiR
Flow	12.45 ls/min (equivalent flow)
Pressure	5.0 bar (a)
Temperature	21.7 °C
Atm. pressure	1010.0 hPa (a)

Calibration and conversion results

Output signal	Customer flow** AiR	Equivalent flow** AiR	Reference flow AiR	Measured deviation*	Measurement uncertainty*
100.42%	12.55 ls/min	12.50 ls/min	12.52 ls/min	-0.13 % Rd	0.4 % Rd
49.89%	6.236 ls/min	6.209 ls/min	6.222 ls/min	-0.20 % Rd	0.4 % Rd
0.00%	0.000 ls/min	0.000 ls/min	0.000 ls/min	-	-



Notes

Flow unit ls/min is defined at conditions 20.00 °C, 1013.25 hPa (a).
* Rated accuracy, measured deviation and measurement uncertainty are specified under calibration conditions in digital mode.
** The customer flow at customer conditions is converted to equivalent flow at calibration conditions using Bronkhorst High-Tech FLUIDAT® software.

Measurement uncertainties are based upon 95% (k=2) confidence limits. Although the item calibrated meets the specifications and performance at the time of calibration, due to any number of factors, this does not imply continuing conformance to the specifications.

Calibrator	G.St.	QC	A.C.
		Date	28 Oct 2014
		Signed	....

MultiCal V2.03 FLUIDAT® V5.73 (Database: 17-03-2003) Report V1.13

SAMPLE III

Bronkhorst®
UK

CALIBRATION CERTIFICATE

FLUID NO. 1 OF 1

CERTIFICATE NO. BHTUK/095182

Calibration by comparison
Calibration date: 28 Oct 2014

We hereby certify that the instrument mentioned below has been calibrated in accordance with the stated values and conditions. The calibration standards used are traceable to national standards of the Dutch Metrology Institute VSL.

Calibrated instrument

Type	Flow controller (D)
Serial number	M13204236B
Model number	F-201CV-10K-ABD-22-V
Rated accuracy*	±(0.5%Rd + 0.1%FS)

Calibration standard

Type	Rotor meter
Serial number	M1207508C
Certificate no.	NMi/G13S2950
Uncertainty	±0.3% Rd

Customer conditions

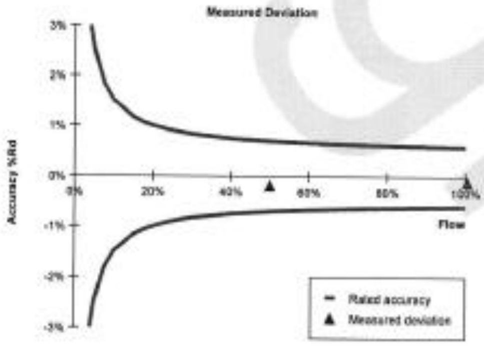
Fluid	AiR
Flow	12.50 ls/min
Pressure	900.0 mbar (a)
Temperature	5.0..40.0 °C

Calibration conditions

Fluid	AiR
Flow	12.45 ls/min (equivalent flow)
Pressure	5.0 bar (a)
Temperature	21.7 °C
Atm. pressure	1010.0 hPa (a)

Calibration and conversion results

Output signal	Customer flow** AiR	Equivalent flow** AiR	Reference flow AiR	Measured deviation*	Measurement uncertainty*
100.44%	12.56 ls/min	12.50 ls/min	12.52 ls/min	-0.10 % Rd	0.4 % Rd
49.90%	6.237 ls/min	6.210 ls/min	6.222 ls/min	-0.19 % Rd	0.4 % Rd
0.00%	0.000 ls/min	0.000 ls/min	0.000 ls/min	-	-



Notes

Flow unit ls/min is defined at conditions 20.00 °C, 1013.25 hPa (a).
* Rated accuracy, measured deviation and measurement uncertainty are specified under calibration conditions in digital mode.
** The customer flow at customer conditions is converted to equivalent flow at calibration conditions using Bronkhorst High-Tech FLUIDAT® software.

Measurement uncertainties are based upon 95% (k=2) confidence limits. Although the item calibrated meets the specifications and performance at the time of calibration, due to any number of factors, this does not imply continuing conformance to the specifications.

Calibrator G.St.

QC A.C.
Date 28 Oct 2014
Signed ....

MultiCal V2.03 FLUIDAT® V5.73 (Database: 17-03-2003) Report V1.13

SAMPLE III

Bronkhorst®
UK

CALIBRATION CERTIFICATE

FLUID NO. 1 OF 1
CERTIFICATE NO. BHTUK/095184

Calibration by comparison
Calibration date: 28 Oct 2014

We hereby certify that the instrument mentioned below has been calibrated in accordance with the stated values and conditions. The calibration standards used are traceable to national standards of the Dutch Metrology Institute VSL.

Calibrated instrument

Type	Flow controller (D)
Serial number	M13204236C
Model number	F-201CV-10K-ABD-22-V
Rated accuracy*	±(0.5%Rd + 0.1%FS)

Calibration standard

Type	Rotor meter
Serial number	M1207508C
Certificate no.	NMi/G13S2950
Uncertainty	±0.3% Rd

Customer conditions

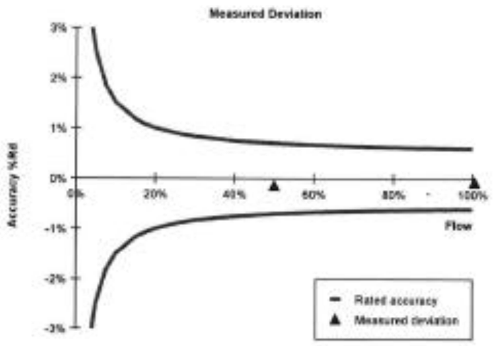
Fluid	**AiR**
Flow	**12.50 ls/min**
Pressure	**900.0 mbar (a)**
Temperature	**5.0..40.0 °C**

Calibration conditions

Fluid	AiR
Flow	12.45 ls/min (equivalent flow)
Pressure	5.0 bar (a)
Temperature	21.7 °C
Atm. pressure	1010.0 hPa (a)

Calibration and conversion results

Output signal	Customer flow** AiR	Equivalent flow** AiR	Reference flow AiR	Measured deviation*	Measurement uncertainty*
100.48%	12.56 ls/min	12.51 ls/min	12.52 ls/min	-0.06 % Rd	0.4 % Rd
49.82%	6.240 ls/min	6.213 ls/min	6.222 ls/min	-0.13 % Rd	0.4 % Rd
0.00%	0.000 ls/min	0.000 ls/min	0.000 ls/min	-	-



Notes

Flow unit ls/min is defined at conditions 20.00 °C, 1013.25 hPa (a).
* Rated accuracy, measured deviation and measurement uncertainty are specified under calibration conditions in digital mode.
** The customer flow at customer conditions is converted to equivalent flow at calibration conditions using Bronkhorst High-Tech FLUIDAT® software.

Measurement uncertainties are based upon 95% (k=2) confidence limits. Although the item calibrated meets the specifications and performance at the time of calibration, due to any number of factors, this does not imply continuing conformance to the specifications.

Calibrator G.St.

QC A.C.

Date 28 Oct 2014

Copy printed by A.C.

MultiCal V2.03 FLUIDAT® V5.73 (Database: 17-03-2003) Report V1.13

9.6 Fuel Analysis

Intertek

ITS Testing Services (UK) Ltd
Analytical Chemistry Laboratory
c/o Rolls Royce, A Site
Victory Rd, Derby DE24 8BJ
Tel: 01332 2 47966
cbederby@intertek.com

Report of Analysis

Job Reference: 2014-DRBY-002373
Job Location: Engine Support
Date Job Created: 22-May-2014
Job Description: Bristol Fuel Samples - Test Plant 105 Engine 01 - 3 Fuel Samples

Client: Rolls-Royce Plc
Contact: Steve Davis
Address: PO Box 31
Derby,
United Kingdom
Customer Reference:
98-148

Sample Summary

Sample Number	Date Completed	Description
2014-DRBY-002373-001	05-Jun-2014	Miscellaneous : Aviation Fuel : - Eng 01 - Test Plant 105 - RT 3.20 - Dated 24/04/2014 - Sample 1
2014-DRBY-002373-002	05-Jun-2014	Miscellaneous : Aviation Fuel : - Eng 01 - Test Plant 105 - RT 10.00 - Dated 30/04/2014 - Sample 1
2014-DRBY-002373-003	05-Jun-2014	Miscellaneous : Aviation Fuel : - Eng 01 - Test Plant 105 - RT 10.00 - Dated 30/04/2014 - Sample 2
2014-DRBY-002373-004	05-Jun-2014	Miscellaneous : Aviation Fuel : - Eng 01 - Test Plant 105 - RT 10.00 - Dated 30/04/2014 - Sample 3
2014-DRBY-002373-005	05-Jun-2014	Miscellaneous : Aviation Fuel : - Eng 01 - Test Plant 105 - RT 12.52 - Dated 01/05/2014 - Sample 1
2014-DRBY-002373-006	05-Jun-2014	Miscellaneous : Aviation Fuel : - Eng 01 - Test Plant 105 - RT 12.52 - Dated 01/05/2014 - Sample 2
2014-DRBY-002373-007	05-Jun-2014	Miscellaneous : Aviation Fuel : - Eng 01 - Test Plant 105 - RT 12.52 - Dated 01/05/2014 - Sample 3

SAMPLE III

Intertek

Report of Analysis

Sample ID: 2014-DRBY-002373-001
Sample Designated As:
Representing: Miscellaneous : Aviation Fuel : Eng 01 - Test Plant 105 - RT 3.20 - Dated 24/04/2014 - Sample 1

Date Taken: 24-April-2014
Date Submitted: 22-May-2014
Date Tested: 05-June-2014
Drawn By: Intertek

Method	Test	Result	Units
DER-LAB-TP-01	Density and Specific Gravity		
	Density @ 15 deg C	793.8	kg/m³
	Specific Gravity @ 15.56/15.56 deg C	0.7942	
DER-LAB-TP-02	Determination of Kinematic Viscosity		
	Test Temperature Manual	20 degree C	
	Kinematic Viscosity	1.661	cSt
DER-LAB-TP-03	Calorific Value		
	Nett Calorific Value	10353	CHU/lb

Sample ID: 2014-DRBY-002373-002
Sample Designated As:
Representing: Miscellaneous : Aviation Fuel : Eng 01 - Test Plant 105 - RT 10.00 - Dated 30/04/2014 - Sample 1

Date Taken: 30-April-2014
Date Submitted: 22-May-2014
Date Tested: 05-June-2014
Drawn By: Intertek

Method	Test	Result	Units
DER-LAB-TP-01	Density and Specific Gravity		
	Density @ 15 deg C	793.8	kg/m³
	Specific Gravity @ 15.56/15.56 deg C	0.7942	

Sample ID: 2014-DRBY-002373-003
Sample Designated As:
Representing: Miscellaneous : Aviation Fuel : Eng 01 - Test Plant 105 - RT 10.00 - Dated 30/04/2014 - Sample 2

Date Taken: 30-April-2014
Date Submitted: 22-May-2014
Date Tested: 05-June-2014
Drawn By: Intertek

Method	Test	Result	Units
DER-LAB-TP-01	Density and Specific Gravity		
	Density @ 15 deg C	793.8	kg/m³
	Specific Gravity @ 15.56/15.56 deg C	0.7942	

Sample ID: 2014-DRBY-002373-004
Sample Designated As:
Representing: Miscellaneous : Aviation Fuel : Eng 01 - Test Plant 105 - RT 10.00 - Dated 30/04/2014 - Sample 3

Date Taken: 30-April-2014
Date Submitted: 22-May-2014
Date Tested: 05-June-2014
Drawn By: Intertek

Method	Test	Result	Units
DER-LAB-TP-01	Density and Specific Gravity		
	Density @ 15 deg C	793.8	kg/m³
	Specific Gravity @ 15.56/15.56 deg C	0.7942	

Report of Analysis

Sample ID: 2014-DRBY-002373-005		**Date Taken:** 01-May-2014	
Sample Designated As:		**Date Submitted:** 22-May-2014	
		Date Tested: 05-June-2014	
Representing: Miscellaneous : Aviation Fuel : Eng 01 - Test Plant 105 - RT 12.52 - Dated 01/05/2014 - Sample 1		**Drawn By:** Intertek	

Method	Test	Result	Units
DER-LAB-TP-01	Density and Specific Gravity		
	Density @ 15 deg C	793.8	kg/m³
	Specific Gravity @ 15.56/15.56 deg C	0.7942	

Sample ID: 2014-DRBY-002373-006		**Date Taken:** 01-May-2014	
Sample Designated As:		**Date Submitted:** 22-May-2014	
		Date Tested: 05-June-2014	
Representing: Miscellaneous : Aviation Fuel : Eng 01 - Test Plant 105 - RT 12.52 - Dated 01/05/2014 - Sample 2		**Drawn By:** Intertek	

Method	Test	Result	Units
DER-LAB-TP-01	Density and Specific Gravity		
	Density @ 15 deg C	793.8	kg/m³
	Specific Gravity @ 15.56/15.56 deg C	0.7942	

Sample ID: 2014-DRBY-002373-007		**Date Taken:** 01-May-2014	
Sample Designated As:		**Date Submitted:** 22-May-2014	
		Date Tested: 05-June-2014	
Representing: Miscellaneous : Aviation Fuel : Eng 01 - Test Plant 105 - RT 12.52 - Dated 01/05/2014 - Sample 3		**Drawn By:** Intertek	

Method	Test	Result	Units
DER-LAB-TP-01	Density and Specific Gravity		
	Density @ 15 deg C	793.8	kg/m³
	Specific Gravity @ 15.56/15.56 deg C	0.7942	

Please note:

The density of samples 001 - 007 were Identical therefore only one sample 001 was analysed for Calorific Value and Viscosity data.

Signed: ______________________ Date: ______________________

Intertek
Danny Sidhu, Level 2 Analyst

ITS Testing Services (UK) Ltd
Sunbury Technology Centre
Unit 'A' Shears Way
Brooklands Close
Sunbury-on-Thames
Middlesex TW16 7EE
Tel : 01932 73 2100
Fax : 01932 73 2113

To:	Liam Mills Intertek Derby Analytical Chemistry Laboratory SIN-A9 Victory Road Derby DE24 8BJ	**Report No.** **Date:** Phoenix No. Order No. Quote No. Date Sample Received Total Cost for Analysis	RT/ELE/13416 03/06/2014 UK760-0016775 Allocate N/A 30/05/2013 £108

Analysis of Jet A1 for Hydrogen Content

Lab Sample No: ELE-260213
Customer Ref. No: 2014-DRBY-002373-001.001

ANALYSIS	RESULTS	UNITS
Hydrogen Content	14.1	% wt/wt

Analysis has been carried out on samples as received, independent of sampling procedure, using the latest versions of all test methods.

Samples will be disposed of after 1 month unless alternative arrangements have been made in agreement with the customer.

Method:
MT/ELE/13 Determination of Hydrogen using a Thermoflash 2000 analyser.

Reported By: Mark Sykes
Mark Sykes
Analytical Chemist

Checked By: A. Geatches
Andy Geatches
Technical Specialist

Contact No.: +44(0)1932 732 118

UKAS TESTING 1049

Registered in England
No. 1408264
Registered Office
Academy Place
1-9 Brook Street
Brentwood
Essex CM14 5NQ

9.7 Gas Analyser Calibration and Cylinder Verification

Rolls-Royce

CERTIFICATE No.	58
PREVIOUS CERT No.	

COMPANY CALIBRATION CERTIFICATE

CUSTOMER	Airlines	LOCATION	Sinfin A
CALIBRATION DEPT	4959	LOCATION	Sinfin A
CIRCULATION			

NEXT CAL. DUE: DAY 1 MONTH 4 YEAR 2024

CAL. INTERVAL: MONTHS OR DAYS

EQUIPMENT/GAUGE INFORMATION

UNIQUE ID	75	CCP REF. No.	5.1, 5.2
REF. No.	40005147268	LCP REF. No.	ECP001
DESCRIPTION	5% CO2/N2	ACCURACY	±2%rdg
		RANGE	
		CALIBRATION CATEGORY	A2

CALIBRATION STANDARDS USED

DESCRIPTION	UNIQUE ID	CAL.VALID UNTIL
IAS2000	1032113	27/11/2013
5% CO2/N2	1	09/11/2019
CO2 NDIR Analyser - Chan 1:CO2	Binos 66	13/05/2014

CALIBRATION UNCERTAINTY

ENVIRONMENTAL CONDITIONS: TEMP. 22 RH% 0

CAL. ERROR REPORTS	NO	~~YES~~ *	
	AS RECEIVED *	PASS	XXXX
	ADJUSTMENTS MADE *	NO	XXXX
CALIBRATION ERROR REPORT No:	FINAL CALIBRATION *	PASS	XXXX

LIMITATION OF USE

CALIBRATED BY: Steve Roe

APPROVED BY: RRTF 331

DATE: 04/09/2014

CAL. DATE: DAY 13 MONTH 5 YEAR 2014

Sheet 1 of 2

617212/3

* DELETE AS APPROPRIATE

Cylinder Verification Report Sheet

Date Of Verification:	13-May-2014
RR Cylinder Number:	75
Gas and Concentration:	CO2 5%
Certified Concentration:	5%

Primary Standard Bottle Details:

RR Cylinder Number:	1
Certified Concentration:	5.02%

Analyser Used Details:

RR Analyser ID:	Binos 66
Instrument Type:	CO2 NDIR

Verification Carried Out By: Steve Roe

Cylinder Verification: PASSED

New Cylinder:

Measured Concentration: 5.00%

Measured Difference (conc units): 0.00%

Measured Difference (% diff): 0.076 %

Pass Criteria: 2.000 %

SAMPLE III

Rolls-Royce

CERTIFICATE No.	51
PREVIOUS CERT No.	

COMPANY CALIBRATION CERTIFICATE

CUSTOMER	Airlines	LOCATION	Sinfin A
CALIBRATION DEPT	4959	LOCATION	Sinfin A
CIRCULATION			

NEXT CAL. DUE: DAY 9 MONTH 7 YEAR 2023 — CAL. INTERVAL: MONTHS ___ OR DAYS ___

EQUIPMENT/GAUGE INFORMATION

UNIQUE ID	70	CCP REF. No.	5.1, 5.2
REF. No.	40004706772	LCP REF. No.	ECP001
DESCRIPTION	5000ppm CO2/N2	ACCURACY	±2%rdg
		RANGE	
		CALIBRATION CATEGORY	A2

CALIBRATION STANDARDS USED

DESCRIPTION	UNIQUE ID	CAL.VALID UNTIL
IAS2000	1032113	27/11/2013
4994ppm CO2/N2	10	13/11/2019
CO2 NDIR Analyser - Chan 1:CO2	Low Range Binos 69	04/09/2013

CALIBRATION UNCERTAINTY

ENVIRONMENTAL CONDITIONS:	TEMP.	22	RH%	0	
CAL. ERROR REPORTS	NO	~~YES~~ *	AS RECEIVED *	PASS	~~XXXX~~
			ADJUSTMENTS MADE *	NO	~~XXXX~~
CALIBRATION ERROR REPORT No:			FINAL CALIBRATION *	PASS	~~XXXX~~

LIMITATION OF USE

CALIBRATED BY: Jim Lowe

APPROVED BY: TF 285

DATE: 04/09/2014

CAL. DATE: DAY 4 MONTH 9 YEAR 2013

Sheet 1 of 2

617212/3

* DELETE AS APPROPRIATE

Cylinder Verification Report Sheet

Date Of Verification:	04-Sep-2013
RR Cylinder Number:	70
Gas and Concentration:	CO2 5000ppm
Certified Concentration:	4994ppm

Primary Standard Bottle Details:

RR Cylinder Number:	10
Certified Concentration:	5002ppm

Analyser Used Details:

RR Analyser ID:	Low Range Binos 69
Instrument Type:	CO2 NDIR

Verification Carried Out By: Jim Lowe

Cylinder Verification: PASSED

New Cylinder:
Measured Concentration: 5006.35ppm
Measured Difference (conc units): 12.35ppm
Measured Difference (% diff): 0.247 %
Pass Criteria: 2.000 %

9.8 Standard Operating Procedures and Checklist for EU/EASA nvPM System

9.8.1 EU/EASA nvPM System Standard Operating Procedure

Document Sections:

System Maintenance and Calibration

Prior and Post engine test series
Annually (minimum)
As required

Operator Guides

System Installation
System Operation
Pre-engine test operation
During engine test operation
Post-engine test operation

9.8.1.1 *SYSTEM MAINTENANCE and CALIBRATION*

9.8.1.1.1 Prior and Post engine test series:

1. Verify the VPR dilution factor (DF2) using CO_2 by allowing the inlet of the VPR to pull a sample (at same inlet flow rate, P and T, as used during engine test) of 100% CO_2 (or other practical CO_2 concentration) $[CO_2\ VPR]_{in}$, from a setup which does not under pressure or overpressure the VPR inlet.

1.1. The results of these checks should be compared against the results of the annual calibration. If a difference of greater than ±10% exists, the VPR should be sent back to manufacturer for service.

1. The dilution factor check requires the following

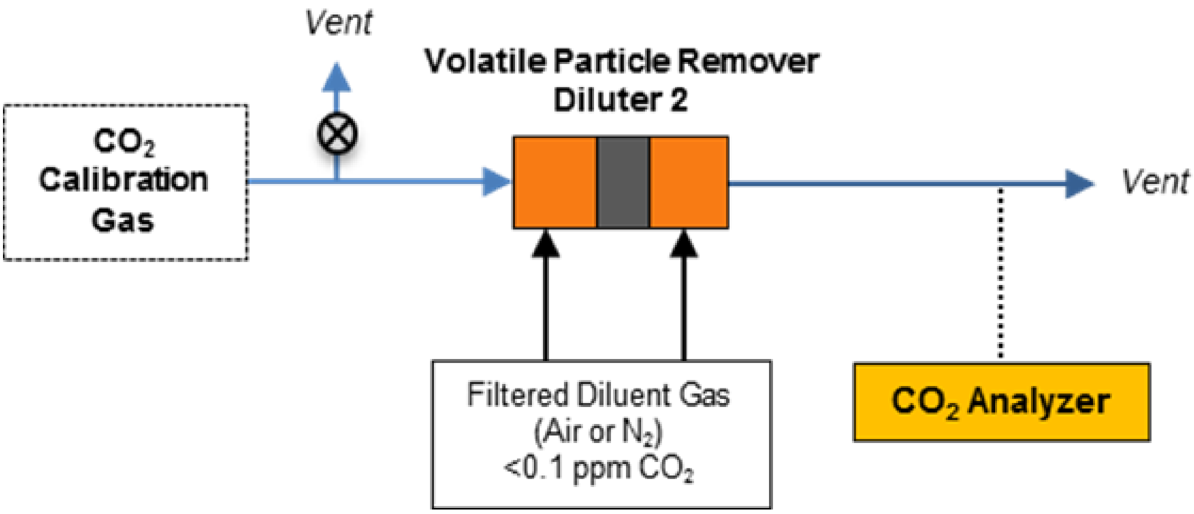
    a. Certified CO_2 calibration gas (CO_2 content of greater than 99% CO_2); and

    b. CO_2 gas analyzer.

2. The setup for the dilution factor check is as follows:

    a. Connect the CO_2 gas analyzer inlet to the exhaust outlet of the VPR with a T-piece to prevent overpressurisation of CO2 sample.

    b. Connect CO_2 calibration gas to the inlet of the VPR using a T-piece and flow control valve to provide a VPR inlet P as same as met on engine test.



3. Once setup, follow the procedures outlined below:

    a. Warm-up the VPR, ensure operating temperatures reached.

    b. Warm-up the CO_2 analyzer accordingly; prepare for data logging.

    c. Begin flowing CO_2 calibration gas to the inlet of the VPR.

    d. Check sample flows for both instruments and ensure they are adequate (typically 5 l/min for VPR; 1 l/min for CO_2 analyzer).

    e. Set the VPR to lowest dilution factor

    f. Adjust flow control valve at VPR inlet to represent sub-ambient engine operation VPR inlet pressure

    g. Sample the VPR exhaust flow with the CO_2 gas analyzer.

h. Begin recording data for both the CO_2 gas analyzer and VPR operational parameters

i. When the CO_2 reading is stable, obtain an average CO_2 concentration over a minimum of 30 seconds.

j. For each VPR dilution setting to be used during engine testing, repeat above sequence.

k. After all measurements are obtained, shut-down instruments following proper procedures.

9.8.1.1.2 Annually (minimum):

1. The cyclone collection pot emptied and cleaned.

2. Flow rate calibration. Use a NMI-traceable flow meter or mass flow controller, individually check the flow rates in the system. At a minimum, these flow rate checks should include the nvPMmi, the nvPMni, the VPR, CO_2 analyzer, and the make-up flow. All flow rates should be within 5% of nominal value.

   Optionally, connect 4PTS to 5PTS and place a calibrated flow meter at 4PTS inlet. Check that the 4PTS inlet flow is within 25 ± 2 SLPM whilst ensuring flow rates in each splitter2 branch are equivalent to those to be used during engine testing.

3. Pressure transducer calibration. Use a NMI-traceable pressure transducer to individually check the pressure measurements in the system (P1 as a minimum). All pressure measurements should be within 2% of nominal value.

4. nvPMmi calibration (and maintenance if required)

5. nvPMni calibration (and maintenance if required)

6. VPR calibration (and maintenance if required)

7. Periodic audit calibration of the CO_2 analyzer shall follow ARP 1256 procedures. The zero gas shall be of the same specification as that used for the Diluter1 diluent (Note: different specification from ARP 1256). The certified span gas concentration shall be between 90 and 100% of analyzer Full Scale.

8. Periodic verification of sample temperature heating.

As required:

1. Over long time usage (typically > 1 year but is dependent on nvPM loading), DF1 will increase. When DF1 is observed to increase and approach the upper range limit

(13) under normal diluter driving pressure (compared to baseline), clean Diluter1 (including orifice nozzle) as per manufacturer guidelines.

2. Follow manufacturer guidelines for Catalytic Stripper replacement interval in the VPR.

3. Replace Butanol in nvPMni as per manufacturer guidelines (typically on a monthly basis) or pre-test basis.

4. Daily MSS Calibration and Checks [assuming hardware is warmed up]:

    a. MSS Change to 'Service' view/tab

    b. Change Online to Service View numerical

    c. Verify Zero is <1.4mV

    d. Verify Resonant Frequency 4150HZ ±100Hz

    e. Verify Cell temperature 52.0°C

    f. Verify Max. Raw Meas. Value is 30-230mV

9.8.1.2 *OPERATOR GUIDE*

9.8.1.2.1 System Installation

1. Install nvPM system and verify compliance using ARP system construction compliance checklist and ARP system installation compliance checklist.
2. Ensure provision of:
   a. DF1 diluent supply (Dry Air or Dry Nitrogen, <10ppm CO_2, HEPA filtered)
   b. DF2 diluent supply (Dry Air, HEPA filtered)
   c. Compressed air – dry and oil free (if required for nvPMmi)
   d. High and low range CO_2 span gas as per ARP1256 specifications
   e. Butanol (grade as per nvPMni manufacturer specification)
3. Install 3PTS within 8m of probe tip, to 2PTS outlet
4. Ensure 5PTS inlet is within 25m of 3PTS outlet
5. Connect 4PTS to 3PTS and 5PTS
6. Connect GTS to 3PTS and Raw CO_2 measurement system
7. Connect nvPMmi and VPR inlets to 5PTS outlets
8. Connect nvPMni inlet to VPR outlet
9. Install relevant system operation/control elements - including power supply, thermocouple cables, DAQ cables, compressed gas tubing (Diluter1, VPR, nvPMmi (if required) and CO_2 analyzer).
10. Ensure pump exhausts are safely vented to atmosphere
11. Connect umbilical to dilution box inlet.
12. Install auxiliary testing equipment to third splitter valve after 5pts oven, nominally designated for the Size spectrometer instruments.

9.8.1.2.2 System Operation

Operate nvPM system and verify compliance using ARP system operation compliance checklist.

9.8.1.2.3 Pre-engine test operation

1. Confirm an open probe sampling valve, so that you can a system stabilisation test can occur by just pulling in ambient air prior to engine test.

2. Day Before Procedures:

    a. Confirm CO2 data acquisition

    b. Check that LII sample cell temperature is set to 60°C.

    c. Leave CO2 analyser ON overnight, so that temperature stabilisation can occur.

    d. Leave APC on overnight, so that temperature stabilisation can occur.

    e. Organise with Test leaders about signalling during test - specifically when to back purge on start-up/shut down, taking ambient measurements for nvPM and the appropriate time to perform a zero/span check of the CO2 analyser (will be within every hour).

    f. APC Butanol levels topped up.

    g. APC Switched 'On'

    h. CO2 Analyser switched 'On'

    i. LII Distilled water Level topped up.

3. Minimum of 1 ½ hours prior to engine start, need to be in on site warming up instrumentation, some of the heaters (e.g. 3PTS outlet) do take a while to stabilise in temperature.

4. Operating Procedure for Hardware On Test day:

    a. Verify Computer status

    b. Verify Router/Switch Status

    c. Verify APC status

    d. Verify CO2 Status

    e. MSS Switch 'On'

    f. LII switch 'On'

    g. MFC x3 Switch 'On'

    h. Brain switch 'On'

    i. Brain 'Enabled'

j. Nitrogen Valve 'Closed'

k. Spill Valve 'Open'

l. Isolation Valve 'Closed'

m. Heated Line temperature Controllers 'On and Enabled'

n. 3PTS Splitter, Diluter and Outlet 'OFF'

o. 4PTS nvPM Line 'On'

p. 2PTS SAMPLE, OEM and Splitter 'On'

q. GTS Line 'On'

r. 5PTS Oven, LII and MSS 'On'

s. Switch Cooling Fans on [Switch at back of unit]

t. Verify Water trap status of CO2 Analyser 'Raw' Channel

u. Supplied Nitrogen and Span gas

v. Verify back purge is 'Closed'

w. Verify Diluter Valve Purge is 'Closed'

x. Span Gas Cylinder 'on'

y. Verify Cylinder pressures [CO2 x2, Nitrogen(Zero)]

z. Verify cylinder supply pressure [Do not exceed 1.5 bar]

aa. Verify individual regulators at back of instrument [~1bar]

bb. Verify Shop Air [MSS, APC and LII][6 bar]

cc. Shop Air bore valve 'Open'

dd. Verify MSS pressure [2 bar]

ee. Verify APC pressure [2 bar]

ff. Verify LII pressure [6 bar]

gg. Nitrogen Dilution Cylinder 'On'

hh. Verify Bank Pressure [may need changing]

ii. Verify Supply pressure [4-5 bar]

5. Perform a sampling system leak check as per ARP1256/1179:

    a. The probe and sample transport system will be checked for leaks by closing the 3PTS spill and isolation valve and temporarily blocking the probe orifices.

    b. Allow the sample transport system to equilibrate at the operating temperature, close the spill control valve and operate the ARP1256 or GTS sample flow pump.

    c. The system shall be satisfactory if no more than 2.0 standard liters (0.07 standard ft^3) pass in a 5 min period. If P1 is located upstream of the isolation valve then it may be used to validate this leak check.

6. Operating Procedure for Software on Test Day [to be done after hardware]:

    a. Sync PC Clock to test bed

    b. Start MSS Software on Internet Explorer

    c. Click 'Remote'

    d. Change User level on MSS to Service Mode (mae483)

    e. Click 'Standby' [20minute wait]

    f. Verify APC Software

    g. If 'On' click Standby' [check sync]

    h. If 'OFF' Switch software 'ON'

    i. Click 'Remote'

    j. Click 'Standby'

    k. Sync LII Clock to PC time [Note: Do Not Start]

    l. Start Brain Software [Particle Diluter]

    m. Start MFC Logging Software [DAQ Central]

    n. Verify Device number [N0808132012]

    o. Click 'Digital'

    p. Verify the 3 MFC lines are visible

    q. Click Device Configuration

    r. Verify Scan rate 1Hz on Channels Tab

s. On Data Tab, Change date of folder and file

t. Start LII Marathon Software

u. Start CO2 Software

7. Logging Start-Ups:

    a. Brain Dilution Valve switch 'Open'

    b. Brain Software - Press 'Start Logging'

    c. Open Nitrogen Regulator [back of rack] to around 2.5 bar

    d. Verify in Brain Software that pressure in Dilution Box is between 2-2.bar [may need tweaking]

    e. LII press 'Start'

    f. Verify Marathon is logging [DO NOT TOUCH LII graph in Marathon]

    g. APC Press 'Measurement' to start logging

    h. Verify log is recording [1xblue square]

    i. MSS Press Measurement to start logging

    j. Verify log is recording [2xblue squares]

    k. Start DAQ Central logging [green arrow]

8. Record the times (and test point number) when OEM is taking an nvPM measurement.

9. OEM call 'Test point'

10. Annex 16 line [nvPM - OEM and SAMPLE system Isolated]

11. nvPM test:

Option A -	Both systems simultaneous
Option B -	1st - OEM [SAMPLE system Isolated]
	2nd - SAMPLE system [OEM system isolated]

    a. Check all system temperature measurements are within specified ranges.

b. Starting the data logging on APC, MSS, Brain, CO2 and mfc's (on USB data logger) as soon as instruments warmed up. Start data logging on LII, SMPS and any other auxiliary test equipment about 1 hour before engine start.

c. Ambient and Zero Tests to occur before Engine run and after engine run.

d. Set conditioner settings to 'Enable no dilution'

e. Ensure that the spill and isolation valves are closed.

f. APC:

   i. Verify 'no errors'

   ii. Select PCRF '100'

   iii. Verify chopper is functional [possible when sampling]

12. Ensure that the GTS flow rate complies with ARP 1256 specifications

13. CO_2 operational checks

14. Confirm that the sample, zero and span inlet flow rates to the CO_2 analysers are in the prescribed operating range

15. Perform span and zero checks as per ARP1256 for the expected CO_2 ranges

16. Mass operational checks

17. Confirm that the inlet flowrate of the nvPMmi is in the prescribed operating range

18. Ensure manufacturer recommended configuration is selected and that operability checks are performed (see relevant SOP)

19. VPR operational checks

20. Confirm that the VPR heated stage has reached 623 +/-15 K

21. Confirm that the inlet flow rate of the VPR is in the prescribed operating range

22. CPC operational checks – Confirm that:

    a. the CPC indicates that the saturator and the condenser have reached their correct operating temperatures.

    b. the inlet flow rate of the CPC is in the prescribed operating range.

    c. the working fluid is at the level required by the manufacturer.

23. Ensure that the make-up flow is set such that the total flow rate in 4PTS is 25 ± 2 slpm. The 4PTS total flow should be validated by summation of the inlet flow rates: nvPMmi, VPR and make-up flow.

24. Perform cleanliness check before nvPM engine emissions data using the following procedure:

    a. Close the isolation valve so that only diluent is flowing through 4PTS.

    b. Ensure flow rates in each splitter 2 branch are equivalent to those to be used during engine testing.

    c. Allow nvPM instrument signals to stabilize

    d. Measure the mass concentration for at least 3 minutes. The average nvPMmi concentration shall be less than 1μg/m^3.

    e. Measure the number concentration for at least 3 minutes at the lowest DF2 setting. The average nvPMni concentration at the lowest DF2 shall be < 1.0 particles/cm^3.

    f. Record the results.

25. Perform an ambient PM measurement representative of engine air inlet before nvPM engine emissions data is obtained. For an enclosed test cell, to achieve representativeness it is recommended that the ambient particle measurement be obtained while the engine is running, a minimum of 5 minutes after engine start-up and just prior to engine shutdown.

26. The ambient air representative engine inlet measurement may be obtained by either:

    a. Sampling through Diluter1 vent (assuming the vent exhaust location is representative of engine inlet air). Turn off the diluent supply to Diluter1 and ensure that the 3 PTS isolation valve is closed; obtain nvPM mass and number measurements. Precautionary note: the diluent heater may overheat. Ensure flow rates in each splitter2 branch are equivalent to those to be used during engine testing.

    b. An additional sampling system conforming to 4 PTS and 5PTS shall be utilized with additional nvPM instrumentation to sample ambient air within 50 m of engine inlet.

27. Allow nvPM instrument signals to stabilize.

28. Ambient mass concentration shall be measured for 3 minutes. Note that the ambient level of PM mass concentration may be below the LOD of the instrument.

29. Ambient number concentration shall be measured for 3 minutes at the lowest diluter 2 setting that will be used during the engine measurements. The average DF2-corrected value of the nvPMni shall be greater than 10 times the value measured for the cleanliness check. If this check fails, verify system operation (valve positions, flow rates, pressures and temperatures) and repeat measurement.

30. Ambient Test point:
    a. Nitrogen Valve 'Closed'
    b. Isolation Valve 'Closed'
    c. Spill Valve: 'Closed' or 'open' depending on pressure in line
    d. Temperature controllers [Diluter, 3PTS Outlet] 'Off'
    e. Record the results.

9.8.1.2.4 During engine test operation

1. Prior to engine start, close the isolation valve and begin back purging through probe using either ambient air or compressed inert gas.
    a. Back Purge:
        i. Isolation valve 'Closed'
        ii. GTS Pump 'OFF'
        iii. GTS Pump Bore Valve 'Closed'
        iv. Spill Valve 'Closed'
2. When engine stable, turn back purge off
3. Start nvPM sampling as required
    a. Sample Test Point:
        i. Isolation valve 'Open'
        ii. Nitrogen valve 'Open'
        iii. Check Pressure on Dilution Box.

iv. Spill Valve: 'Closed' or 'Open' depending on pressure in line

v. [Note: above 3-5mbar Spill 'Open' / concurrent with other system then >10mBar]

vi. GTS Valve 'Open'

4. GTS Pump 'On'

5. If any part of the sampling system has been replaced or cleaned, the new part should be exposed to engine exhaust for at least 30 minutes to ensure all internal surfaces are conditioned. This can be achieved at any engine power condition.

6. Calculate and report DF1 using raw and diluted CO_2 values

7. Adjust spill valve to maintain DF1 to be in correct operational range (8 to 13).

8. The CPC must remain in the single particle counting mode. Monitor the CPC number concentration; adjust DF2 to maintain CPC raw concentrations within single particle counting mode (typically below 10,000 particles/cm^3) and where possible within the calibrated range.

9. Ensure nvPMmi, nvPMni and CO_2 signals are stable

10. Record 30 s average nvPM instrumentation and system data for each stable engine operating condition.

11. Calculate 30 s average EImass and EI number using typical fuel values

12. Calculate 2σ variation of nvPMmi, nvPMni, CO_{2_dil1}, EIm and EIn.

13. Monitor system and instrument parameters to check for failures.

14. Perform nvPM cleanliness checks periodically during engine test

15. Perform hourly zero and span checks for the CO_2 analyzer.

16. At end of nvPM sampling close the isolation valve and spill valve if necessary.

    a. Isolation:

        i. GTS Pump 'OFF'

        ii. GTS Pump Bore Valve 'Closed'

        iii. Isolation valve 'Closed'

        iv. Spill Valve 'Closed'

17. Zero test point:

    b. Isolation valve 'Closed'

    c. Spill Valve: 'Closed' or 'open' depending on pressure in line

18. Prior to engine shutdown, close the isolation valve and begin backpurging through probe using either ambient air or compressed inert gas.

9.8.1.2.5 Post engine test operation

1. Perform cleanliness check after nvPM engine emissions data obtained using the following procedure:

    a) Close the isolation valve so that only diluent is flowing through 4PTS.

    b) Ensure flow rates in each splitter 2 branch are equivalent to those to be used during engine testing.

    c) Allow nvPM instrument signals to stabilize

    d) Measure the mass concentration for at least 3 minutes. The average nvPMmi concentration shall be less than 1µg/m^3.

    e) Measure the number concentration for at least 3 minutes at the lowest DF2 setting. The average nvPMni concentration at the lowest DF2 shall be < 1.0 particles/cm^3.

    f) Record the results.

2. Perform an ambient PM measurement representative of engine air inlet after nvPM engine emissions data is obtained.

    For an enclosed test cell with stagnant air, the ambient particle measurement shall be obtained while the engine is running, a minimum of 5 minutes after engine start-up and just prior to engine shutdown.

    a) The ambient air representative engine inlet measurement may be obtained by either:

        i. Sampling through Diluter1 vent (assuming the vent exhaust location is representative of engine inlet air). Turn off the diluent supply to Diluter1 and ensure that the 3 PTS isolation valve is closed; obtain nvPM mass and number measurements. Precautionary note: the diluent heater may overheat. Ensure flow rates in each splitter2 branch are equivalent to those to be used during engine testing.

ii. An additional sampling system conforming to 4 PTS and 5PTS shall be utilized with additional nvPM instrumentation to sample ambient air within 50 m of engine inlet.

b) Allow nvPM instrument signals to stabilize.

c) Ambient mass concentration shall be measured for 3 minutes. Note that the ambient level of PM mass concentration may be below the LOD of the instrument.

d) Ambient number concentration shall be measured for 3 minutes at the lowest diluter 2 setting that will be used during the engine measurements. The average DF2-corrected value of the nvPMni shall be greater than 10 times the value measured for the cleanliness check. If this check fails, verify system operation (valve positions, flow rates, pressures and temperatures) and repeat measurement.

e) Record the results.

3. Stop data logging.

4. Power down all subsystems:

a) system heaters

b) pumps and flow controllers

c) Measurement analysers (CO_2, nvPMmi, VPR, nvPMni)

d) Data logging systems

5. Turn off compressed gas supplies, vent any excess pressure.

   a. DF1 Diluent

   b. DF2 Diluent (VPR)

   c. Compressed air (if required for nvPMmi)

   d. CO_2 span gases

6. Back up all new data files.

9.8.2 EU/EASA nvPM system Checklists

System Installation Checklist

System Installation checklist		Yes (tick)
Ensure provision of:		
	DF1 diluent supply (Dry Air or Dry Nitrogen, <10ppm CO_2, HEPA filtered)	
	DF2 diluent supply (Dry Air, HEPA filtered)	
	Compressed air - dry and oil free (if required for nvPMmi)	
	High and low range CO_2 span gas	
	Butanol	
Install 3PTS within 8m of probe tip, to 2PTS outlet		
Ensure 5PTS inlet is within 25m of 3PTS outlet		
Connect 4PTS to 3PTS and 5PTS		
Connect GTS to 3PTS and Raw CO_2 measurement system		
Connect nvPMmi and VPR inlets to 5PTS outlets		
Connect nvPMni inlet to VPR outlet		
Install relevant system operation/control elements - including:		
	Power supply	
	Thermocouple cables	
	DAQ cables	
	Compressed gas tubing - Diluter1, VPR, nvPMmi (if required) and CO_2 analyzer	
Ensure pump exhausts are safely vented to atmosphere		

System Operation Checklist

Test	Criteria	Results	Pass (tick)
Sampling System leak check	$\leq$ 2.0 liters in 5 min	___ liters in 5 min	
Inlet flow check	25 ± 2 lpm	lpm	
nvPMni Flow Rate	Instrument Dependent: ___ lpm	___ lpm	
nvPMmi Flow Rate	Instrument Dependent: ___ lpm	___ lpm	
CO_2 Analyzer Flow Rate	Instrument Dependent: ___ lpm	___ lpm	
Make-up Flow Rate	Instrument Dependent: ___ lpm	___ lpm	
CO_2 Analyzer Span Check	___ low CO_2 conc true ___ high CO_2 conc true	___ low CO_2 conc ___ high CO_2 conc	
Initial Zero/ Cleanliness Check	$\leq$ 3 µg/m^3 or 0.003 mg/m^3	3 min. mass = ___ µg/m3	
	$\leq$ 0.5 cm^{-3}	3 min. num = ___ cm^-3	
Initial Ambient Concentration	mass conc	3 min. mass = ___ µg/m^3	
	number conc	3 min. num = ___ cm^{-3}	

SAMPLE III

Post Test Checklist

Test/Operation		Criteria	Result	Pass/Done
Cleanliness check				
	Mass analyzer concentration	3 minute average $\leq 1\ \mu g/m^3$	_______ $\mu g/m^3$	
	Number analyzer concentration (DF2 corrected)	3 minute average $\leq 1.0\ p/cm^3$	_______ p/cm^3	
Ambient nvPM measurement				
	Mass analyzer concentration		_______ $\mu g/m^3$	
	Number analyzer concentration (DF2 corrected)	10 times > Cleanliness result	_______ p/cm^3	
Stop system data logging				
Back up all new data files				
Power down all subsystems:				
	system heaters			
	pumps and flow controllers			
	Measurement analysers (CO_2, nvPMmi, VPR, nvPMni)			
	Data logging systems			
Turn off compressed gas supplies, vent any excess pressure				
	DF1 Diluent			
	DF2 Diluent (VPR)			
	Compressed air (if required for nvPMmi)			
	CO2 span gases			

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