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

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Disclaimer

Disclaimer

This study has been carried out for the European Aviation Safety Agency by an external organisation and expresses the opinion of the organisation undertaking the study. It is provided for information purposes only and the views expressed in the study have not been adopted, endorsed or in any way approved by the European Aviation Safety Agency. Consequently it should not be relied upon as a statement, as any form of warranty, representation, undertaking, contractual, or other commitment binding in law upon the European Aviation Safety Agency.

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The majority of the personnel involved in the SAMPLE III.03 / A-PRIDE 5 SR Technics engine testing are shown in Figure 1 below.

Figure 1 SAMPLE III.03 (A-PRIDE 5) experimental team

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}: **SC03** Implementing Framework Contract N^{o}: **EASA.2010.FC10**.

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

- The " draft working document" had to be finalised in early 2013,
- PM data gathered during previous test campaigns needed to be analysed in more detail in order to respond to outstanding issues that were raised during SAMPLEIII SC02 engine tests and subsequently during the SAE E-31 PM subcommittee meeting in September 2012,
- Additional elements had to be built into the SAMPLE III sampling system; and a thorough validation required during dedicated engine tests, in order to permit the SAMPLE III system to become a mobile reference sampling and measurement system for the European Union,
- Data needed to be gathered 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: design, manufacture and appraisal of the SAE E31 AIR6241 compliant system for measurement of non-volatile particulate matter at the exhaust of large-scale (>26.7 kN thrust) gas turbine aircraft engines, provide support in drafting the "draft working document" (now called AIR6241) that will lead to the Aerospace Recommended Practice (ARP) for ballot, perform analysis of PM data gathered during previous SAMPLE test campaigns, acquire and analyse additional engine PM data, all in support of the development of a robust 'ballotable' ARP which will subsequently enable a non-volatile particulate matter (nvPM) certification requirement.

Key results and recommendations from this study include:

1. The SAE E31 nvPM AIR 6241 was prepared in time for a ballot prior to the SAE E31 2013 annual meeting
2. AIR6241 was successfully balloted by SAE E31 after technical and editorial comments implemented
3. The SAE E31 nvPM ARP is currently on schedule for end of 2014. The ARP's delivery will depend upon proof of robust measurement and operational testing of the proposed nvPM system by engine manufacturers.
4. Data from SAMPLEIII SC02, suggests a repeatability of 20% or better for nvPM mass and 30-40% for nvPM number if considering repeats on a particular engine.
5. Thrust levels can be used to consider total nvPM variability on repeated engine data, however, it is likely that engine manufacturer proprietary parameters (such as T30) will need to be plotted to fully assess nvPM engine variability.
6. Analysis of existing data indicates that it is not obvious, due to conflicting combustion physical processes (related to combustor inlet Temperature and Pressure), whether ambient corrections are required for nvPM. There is some limited evidence that elevated ambient temperature may reduce PM.

7. Engine-to-engine variability data may or may not encompass variations in ambient conditions
8. Combustion rig testing (with AIR6241 instrumentation) is likely required to consider the effects of Fuel-Air-Ratio (FAR) and P30 (inlet combustor pressure) independently
9. Consideration of variability expectations for engine-to-engine need to be considered by regulators and funding bodies, in order that regulated values including statistical compliance can be adopted.
10. More engine testing is required with AIR6241 sampling/measurement systems to assess engine-to-engine variability.
11. An EU/EASA mobile reference system was constructed in compliance with both AIR6241 and SAE E31 recommendations for a non-volatile PM reference system
12. Three AIR6241 compliant systems, 2 mobile (EU/EASA and North American) and 1 fixed (Swiss) were successfully inter-compared (to be known as 'reference' systems) on a CFM56-7B26/3 engine PM source.
13. Long term inter-comparability of compliant reference systems is needed.
14. AIR6241 Primary Dilution Factor (DF1) range limits were met for the EU/EASA system across all CFM56-7B26/3 engine conditions during the Zurich testing. This was achieved by controlling the diluent pressure and spill valve position upstream of Diluter 1.
15. It was not always possible with the EU/EASA reference system to keep the GTS flow rates within existing Annex 16 specifications, whilst ensuring DF1 was in AIR 6241 specification. This was particularly observed at low engine power, thus simultaneous gas, smoke and nvPM measurements would not be possible with the Zurich probe geometry tested.
16. Discrepancies were observed in the three reference systems for DF1 during the multiple system testing. Typically the Swiss system was significantly lower than the EU/EASA system and the North American system slightly higher (sometimes outside the AIR6241 specified range). However the effect of simultaneous sampling of multiple systems will have had an effect on DF1 compared to what may be achieved during single system testing.
17. During the small engine testing in Derby it was generally possible to meet DF1 range specifications for the small thrust engine (with the single point probe). However, it was observed that at the lowest engine thrust the DF1 increased to 13.2 (just outside the specified 8 to 13 range). As such the authors make the following recommendations:
    - DF1 diluent pressure is added to AIR6241 methodology (noting that it should be proven for a specific diluter, what is the lowest workable diluent pressure with 25 slpm being drawn from the diluter exit without sucking in ambient air through the vent)
    - Assess increasing AIR6241 compliant DF1 range to 8 to 14, noting that as more engine manufacturer's engines and probe/rake designs are tested, the range may need to be extended further prior to the finalised ARP.
18. During the AIR6241 system cleanliness (and leak) checks the mass instruments met specification; however, the number specification was unable to be met (on both the EU/EASA and North American systems). It was proven that the rotary diluter seals of the AVL APC were the leak source, the cause being the lower APC inlet sample pressure witnessed on both the EU/EASA and North American system compared to the Swiss system.

   - Recommend that the AIR6241 zero limit be increased at least as a minimum from 0.5 to 1 particles/cm^3 (for the lowest DF2 used for the measurement), noting that at even at 5 particles/cm^3 the additional uncertainty would only be 0.25% when compared to the AIR6241 existing traceable CPC calibration range.
19. Ambient mass and number data was obtained as per AIR6241 specifications. However, there is inconsistency in the length of time required by AIR6241 for ambient (and zero) measurements (3 minutes) compared to engine measurements (30s)
20. During the VPR performance check, it was observed that there was a small impact of inlet sample pressure on the measured Dilution Factor (DF). The instrument dilution settings were only just within the AIR6241 10% limits. At this time it is unknown why the DF measured during the performance check were different to those quoted during the calibration certification. As such the authors recommend that:
   - The VPR performance check is conducted at a sample inlet pressure condition representative of system operation.
   - During future system measurements, the VPR DF check is monitored over time to check for long term drift.
21. It was observed that PM data took numerous minutes to stabilise, (typically ~2 to 4 minutes) after the engine reached a new power condition. The judgement for stable emissions conditions has historically always been performed by visual assessment of real time gaseous data. However, an expression using 2 standard deviations is proposed as a possible candidate for verifying w a data-point stable. The authors thus recommend.
   - SAE E31 should consider whether visual observation or a mathematical expression should be used to verify PM stability.
22. Large spikes in mass concentration were observed at the maximum continuous engine condition, on the ‘multi-point’ cruciform probe. These spikes were attributed to ‘particle shedding’ (similar to observations in SAMPLE I rig measurements) from the internal probe surfaces.
23. It was observed that the nvPM number concentration could vary during the evaporation tube/ CS heating cycle. Therefore the authors recommend
   - Pre-heating the evaporation tube / catalytic stripper to at least 360°C for several hours after receiving the instrument back from calibration, before cooling back to 350ºC.
24. No impact of DF1 sensitivity was observed on the CFM56-7B26/3 engine over a range of engine power conditions. However, DF1 nvPM number sensitivity was clearly observed (statistically significant for the AIR6241 specified range) on the small helicopter engine at the higher power conditions. The size distribution analysis suggests that coagulation was occurring. Though the Gnome engine has a legacy-type combustor it is unknown where the coagulation threshold margin lies across legacy/ modern/ development combustor type technology.
25. More investigation and datasets are required to assess the impact on the measured particle number concentration and future line loss correction uncertainties, accounting for possible coagulation. Therefore the authors recommend:
   - During future engine PM testing (single or multiple measurement system), PM data is obtained at different DF1 (by altering diluent pressure) at a steady state condition across a range of engine powers. If possible at the highest DF1 achievable with the system.

- the impact of coagulation is considered for possible future sampling system line loss correction

26. The extent of coagulation in the first section of sampling line between probe inlet and diluter inlet is unknown, for all the engines tested. At the lower engine power conditions (lower number concentrations) data from R-R Gnome test seems to confirm if probe inlet number concentrations are greater than ~$3x10^7$ $\#/cm^3$ coagulation is likely in that section of line (dependent on residence time in 1PTS/2PTS sections).
27. Neither the nvPM mass or number concentrations were statistically sensitive to DF1 diluent composition (Synthetic Air or Nitrogen)
28. Successful online DF2 measurements via CO_2 were performed. No significant differences were observed between online DF2 and pre-test DF2 check values (variance was within AIR6241 10% allowance specification for the VPR DF check). The authors note that the online methodology could be improved if the CO_2 analyser and calibration gas specifications were improved beyond ARP1256 requirements.
29. The 3 reference PM number instruments were sent to the instrument manufacturer for calibration in accordance to AIR6241 specifications, as a result instrument penetration limits needed to be reduced by the SAE E31 prior to the final document ballot, in order to meet conformance.
30. During the reference nvPM instruments annual calibrations, several calibration issues were encountered at the (ISO 17025 compliant) qualified calibration laboratory. As such the only VPR/CPC in full AIR6241 compliance was the North American system. Therefore the authors recommend:
    - VPR/CPC suppliers develop a specific aviation specification calibration certificate. This should include close liaison with SAE E31 to produce a recommended calibration procedure/certificate.
31. Significant differences were observed between the EU/EASA and the other two reference CPC linearity gradients. It is noted that the North American and Swiss CPC's were calibrated concurrently and all CPC's are of the same model. It was observed that all the reference CPC displayed increased offset from linearity at the lowest traceable number limit (2000 particles/cm^3). Non-linearity is not expected therefore the authors recommend:
    - That further work (to include CPC manufacturers) is performed to assess whether the 10% linearity limit can be tightened towards 3 or 4%.
32. The CPC lower size cut-points (at D_{10} & D_{50}) were significantly different between the EU/EASA and other two reference systems, again it is noted that the North American and Swiss CPC's were calibrated concurrently and all CPC's are the same model. It is thus recommended:
    - CPC calibrated lower size cut-points (D_{10} & D_{50}) are included in a possible future PM system continuous loss function correction.
33. It was observed that altering the PCRF setting of the VPR changed the dilution corrected number concentration, though the variance was within the overall number measurement expected uncertainty, but did always move the measured number in the same direction. Therefore it is recommended:
    - That where possible on future PM system engine testing, an evaluation of different dilution settings should be performed at steady engine condition(s) to ensure that the variance stays within the expected measurement uncertainty.
34. At engine powers of 30% and below, it was not possible to operate the system at a combined (DF1 plus DF2) dilution factor so that the PM number measurement (CPC

raw count) was in the AIR6241 traceably calibrated range. Therefore it is recommended that:

- Investigate implementation of a traceable calibration methodology for <2000 particles/cm^3. For example, ISO 27891 Annex I (in final draft expect to be published 2014)
- And/or assess the increase in number measurement uncertainty measurements if nvPM number counts are obtained below the traceable limit.
- Investigate if commercially available VPR's could be converted to provide a lower DF2.

35. Overall the number measurement reproducibility between the 3 reference systems was generally within theoretical measurement uncertainty predictions (18 to 22%); However these 3 units were nominally identical so the uncertainty permitted by AIR 6241 may be higher than this.
36. Various biased discrepancies between the 3 systems were observed which should be further investigated, as the observed number data contradicted pre-test miniCAST comparisons. Therefore the authors recommend
    - System inter-comparisons are performed between different PM number instrument manufacturers (VPR and CPC).
    - system PM instrumentation are operated under environmental conditions recommended by manufacturers
37. All PM mass instrumentation met AIR6241 calibration performance specifications
38. It was observed that utilising diaphragm pumps in EU/EASA and North American systems caused the AVL MSS instrument to experience significant noise interference, caused by fluctuations in the sample pressure. It was noted that noise was not observed on the Swiss MSS due to the use of a buffer volume upstream of the make-up flow pump, thus this methodology was applied to both the North American and EU/EASA reference systems for the Zurich engine testing. Changing the make-up and LII pump from a diaphragm type to rotary type (for the small engine testing) removed the AVL MSS noise interference without having to install a buffer volume between the pump and instrumentation. It is thus recommended:
    - That AIR6241 instrumentation and make-up pumps specification should either limit the type of pump utilised, or control pressure fluctuations using damping volumes if an MSS is utilised in the PM measurement system. If the pressure fluctuation impact limit is known for the MSS, a performance based sampling specification could be implemented instead.
39. The AVL MSS must be run in service mode to obtain PM mass measurements on an AIR6241 compliant system if the instrument inlet pressure is lower than -80 mbarG (as observed on both the EU/EASA and North American systems). The MSS can only be used in normal conventional standard operation at instrument inlet pressures higher than -80 mbarG.
40. On Pre and Post engine test miniCAST comparisons, all the mass instruments agreed within measurement uncertainty expectations (11%).
41. Deviations larger than uncertainty expectations were observed between the mass instruments on engine PM inter-comparisons. Initial estimates of AIR6241 mass methodology uncertainty could be as large as 40 to 60% at low (<100 µg/m^3 mass instrument inlet concentrations), which reduces to ~20% at higher (>100 µg/m^3 mass instrument inlet concentrations).
42. There is some evidence that similar mass instrument types (LII vs MSS) agree better than comparing different methodologies.

43. The discrepancies observed between the PM sources (gas turbine engine and miniCAST) are under further investigation by the SAE E31 mass team including AVL.
44. At CFM56-7B26/3 engine powers of 30% and below, the mass concentration at the instrument inlet was below the AIR6241 specified 3xLOD (9 µg/m^3).
    – Require feedback from CAEP to assess whether to spend additional technical time and resource to achieve PM mass measurements at lower engine powers.
    – Operate/calibrate mass instrumentation below the existing AIR6241 LOD.
    – Possibly re-investigate feasibility of nvPM mass measurement on the GTS line
45. Representative PM data was obtained from the CFM56-7B26/3 engine. nvPM EI and size distribution data was consistent with previous PM trends observed in typical modern 'rich burn' engine tests in SAMPLE I, II & III campaigns. The maximum EI mass (~75 mg/kg) and largest mean particle sizes (~45 nm) were observed at the highest engine conditions. The maximum EI number (~3e14 #/kg) was observed at high powers but not at the highest. Both the lowest EI mass (which was below LOD <0.1 mg/kg) and EI number (~2.1E13) #/kg) were observed at engine conditions slightly above ground idle and had the smallest mean particle sizes (~16 nm). The EI number and EI mass increased slightly at ground idle conditions. As in line with AIR6241, these EI's are not corrected for particle loss in the system.
46. nvPM emissions data was obtained on a small turbo shaft helicopter engine Rolls-Royce Gnome. Again a similar trend was observed with the maximum EI mass (~450 mg/kg) and largest particle sizes (~43 nm) observed at the highest engine conditions. The maximum EI number (~5E15 #/kg) was also observed at the highest engine power. Noting that the true maximum EI number would be higher due to the observed coagulation effect. Both the lowest EI mass (~18 mg/kg) and EI number (~1.4E15) #/kg) were observed at low engine power conditions above ground idle and had the smallest particle sizes (~24 nm). The EInumber and EImass increased slightly at ground idle conditions. As in line with AIR6241, these EI's are not corrected for particle loss in the system.

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 defining a new methodology for the measurement of aircraft non-volatile Particulate Matter (PM) emissions. Although the report does not provide a finalised established methodology, 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 procedures for non-volatile PM measurement in terms of mass and number.

Key Themes of the report are

- Assess whether existing nvPM data sets are able to steer decision making into the effect of ambient conditions on nvPM formation emitted by 'modern' gas turbine engines.
- Design and manufacture an AIR 6241 and SAE E31 compliant 'mobile reference system'
- Compare the SAMPLE III system with other 'reference' systems to determine typical measurement variations facilitated by AIR 6241
- Assess the validity and operability of parameters specified in AIR 6241 and ascertain whether it is possible to improve the methodology prior to it being turned into an ARP
- Measurement of other 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

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 PM. 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 PM 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 >26.7kN. 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 has been working on developing appropriate sampling and measurement methods for aircraft non-volatile PM emissions, but has 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 PM 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) are needed for engine manufacturers to compare to, at their own test facilities. Within SAMPLE III (SC03) a European 'mobile reference' system is being developed for this task, whilst also obtaining an initial system comparison datum, by undertaking comparative engine testing with both the North American (mobile) and Swiss (fixed) reference system, which will provide a baseline for expectations of future engine manufacturer system inter-comparisons.

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 **SC03.** It should be noted that in order to successfully meet the objective of Task 3a below, specific contract **SC04** was required and successfully completed.

The main purpose of this specific contract (**SC03)** is to apply the knowledge gained from the previous years of study (SAMPLE, SAMPLE II, SAMPLE III SC01& SC02) along with that shared within the SAE E31 Committee gained from full-scale engine testing, in order to check the practicability, variability and representativeness of the SAE E31 AIR 6241 compliant sampling system whilst developing 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: Finalise “draft working document” and improve content for the development of the Aerospace Recommended Practice (ARP) via the creation of an AIR.

Task 2: Analysis of data gathered during previous test campaigns

Task 3a: Construct SAMPLE III sampling system as an ARP compliant system to be a mobile reference sampling system for the European Union

Task 3b: Cross-Validation of multiple ARP compliant systems at SR Technics or RR Derby

Task 4: Acquisition and analysis of additional engine data

4. Task 1: Finalisation of SAE E31 nvPM Draft Working Document

4.1 Introduction

Significant progress was made within SAE E31 during SAMPLEIII SC02 to develop and produce a “draft working document” (DWD) for non-volatile PM measurement methodology in aircraft engine exhaust. In SAMPLEIII SC03 the consortium were tasked to assist in the developing the draft working document towards an ARP.

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

Dr. Mark Johnson is a member of the SAE E31 PM ARP Co-ordination group, which has aided in ensuring a co-ordinated technical, regulatory and policy perspective to the decisions taken in the development of the current working document.

Due to the progress made in the development of the DWD, and to ensure OEM confidence in making sound business purchase and engine test opportunity decisions, a referenceable official document was needed. Thus SAE E31 decided to create an AIR (Aerospace Information Report) based upon the DWD. This document would allow substantial robust testing of the methodology by both researchers and OEM’s (Engine Manufacturers) and create datasets to establish measurement uncertainty prior to the ballot of an ARP.

A time line highlighting the route forward for the development of a ‘ballotable’ ARP was presented by Dr Mark Johnson during the SAE E31 annual meeting (Ispra 2013) and is presented below in Figure 2. It includes the key engine test campaign (A-PRIDE 5) discussed in detail in Chapter 7 of this report.

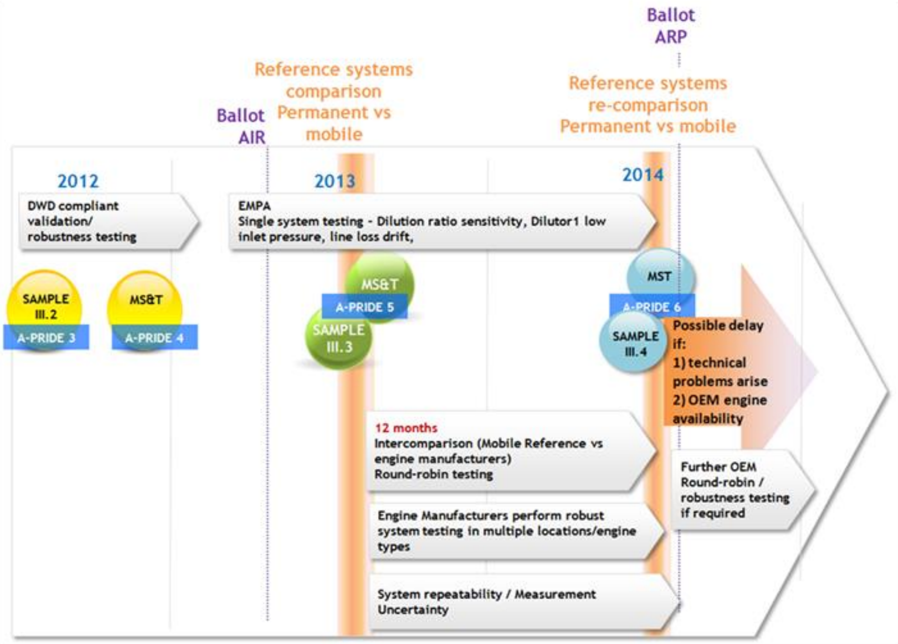


Figure 2 Proposed Timeline from DWD to ARP

It can be seen that if there is sufficient funding available, the balloted ARP is predicted to be ready by the end of 2014, with a caveat that this date is prone to slippage if there are unforeseen technical problems to overcome (or if OEM engine tests are not available).

Note that an additional SAE E31 Technical Team has been established to define a possible methodology for sampling system line loss correction. The timeline for this methodology is Q2 2015 (however, this is not required for a balloted nvPM ARP).

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

Dr Mark Johnson is team lead of the sampling section of the draft working document and sponsor of AIR6241 and subsequently the final ARP. He has been responsible for guiding the sampling team discussions in bi-weekly tele-conferences along with leading discussion at SAE E31 Committee and PM sub-committee meetings.

Knowledge gained during these meetings has facilitated the sampling section of AIR 6241 to be completed within SAE-E31 and edited by Dr Mark Johnson. 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.

As sampling team lead, Dr Mark Johnson has been responsible for drafting the sampling section of the aforementioned PM AIR. 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 a ballotable ARP.

In order to ensure that the appropriate technical issues were being addressed, Dr Mark Johnson was test co-ordinator of the SAMPLE III, SR Technics test campaign (SAMPLE III.03 campaign). This role not only involved campaign planning and system building (along with Dr Andrew Crayford) and co-ordinating the actual test, but also liaising with many other parties involved in the testing. These included Empa (engine lease, test-bed and running costs; operation of FOCA/Empa AIR6241 compliant PM sampling system and provision of calibration gases), SR Technics (engine lease, engine performance, engine running and test-bed system installation), MS&T (operation of FAA/EPA AIR6241 compliant system and volatile measurements), NRC (Annex16 mass instrument and instrument comparisons) and AVL (APC inter-comparisons and MSS expertise). The test was observed by Daniel Jacob (US regulator) and Theo Rindlisbacher (Swiss regulator). All of which ensured a sound validation of the three reference AIR6241 compliant systems.

4.3 Task 1b: Sponsorship of AIR 6241

Dr Mark Johnson fulfilled the role of sponsoring AIR6241 to bring the draft working document into an official SAE document through an SAE E31 committee ballot. This entailed coordinating not only with the other SAE E31 team leads to produce a draft AIR document but also liaising with the SAE organisation throughout the ballot process.

AIR6241 document timeline:

At the SAE E31 PM subcommittee meeting (21^{st} to 24^{th} Jan 2013), the subcommittee approved that the DWD was ready to be submitted as an AIR.

- 29^{th} January, AIR 6241 document number created by SAE.

- 15^{th} March, the initial AIR draft was merged by Dr Rick Miake-Lye and circulated for review

- 25^{th} March, numerous comments received and addressed by Dr Mark Johnson in conjunction with other Team leads

- 17^{th} April, AIR6241 submitted for 28 day SAE E31 committee ballot (including multiple appendices)

    - 15^{th} May, ballot closed. 28/30 members voted - Result: 23 Approved, 3 Disapproved, 2 Waived

The 3 disapprovals were related to two technical comments. In addition a large number of non-technical comments were received. Non-technical comments were addressed by Dr Mark Johnson.

- 10^{th} to 13^{th} June, at annual SAE E31 meeting, successful agreement on technical and non-technical comments. Comments implemented in to AIR.

- July 16^{th} AIR 6241 submitted for 14 day affirmation ballot

- July 30^{th} No ballot comments received, AIR6241 successfully balloted.

Currently AIR6241 is going through the formality process of the SAE council ballot prior to publication of the document.

4.4 Conclusions of Task 1

1. The SAE E31 nvPM AIR 6241 was prepared in time for a ballot prior to the SAE E31 2013 annual meeting
2. AIR6241 was successfully balloted by SAE E31 after technical and editorial comments implemented
3. The SAE E31 nvPM ARP is currently on schedule for end of 2014. The ARP's delivery will depend upon proof of robust measurement and operational testing of the proposed nvPM system by engine manufacturers.

5. Task 2: Analysis of previous experimental data

5.1 Introduction

To help address nvPM outstanding issues the consortium were tasked to re-work existing SAMPLE (I, II & III) data.

Analysis of PM engine-to-engine variability data was performed, by suitably qualified, combustion emission specialists at Rolls Royce, using existing SAMPLE datasets (which includes engine data from the SR Technics facility in Zurich, provided by FOCA). To help plan future test campaigns within the CAEP nvPM certification process, the engine variability analysis with conclusions were presented to CAEP WG3 PMTG meeting in Madrid, September 4th to 6th 2013 by Rolls-Royce combustion emission specialist Paul Madden.

Comparison analysis of previous dilution sensitivity experimental data from SAMPLEIII SC02 is discussed in section 7.3.8 where experiments were specifically performed to help assess this outstanding PM ARP technical issue.

5.2 Engine-to-Engine variability and effect of ambient conditions using SAMPLEIII SC02 data

A large amount of engine and nvPM data was obtained during the EASA funded ‘SAMPLE III SC02: Contribution to Aircraft Engine PM Certification requirement and Standard’ project carried out at SR Technics in Zurich in 2012. The data collected during the campaign for each tested engine was as follows:

- Engine data
- System data
- Ambient data
- DMS data
- LII data (if available)
- Gaseous Emissions data (provided by FOCA/Empa)
- Smoke Data

These data sets, along with their respective timestamps, were merged into single Microsoft Excel spread-sheets (in multiple tabs) by FOCA. The data in the spread-sheets consisted of all the engine conditions run during the testing period. Of interest are only the periods where the engine conditions were steady for a suitably long period of time. Over each of these time periods, data was gathered and averaged for the relevant engine, system and emissions parameters. A list of the relevant datasets of interest to be extracted during appropriate periods was produced and these formed the majority of the column headings in the final analysed data spread-sheet.

Processing large datasets 'by hand' through Excel would have been time consuming with a high scope of error. Thus, to expedite the process, scripts were written in MATLAB to automate the process with a minimal requirement for user input. This also added additional benefits of introduced flexibility, whilst facilitating data quality checking and filtering capabilities.

Due to the complexity of the measurements and time constraints during testing, data quality issues could only be identified during post-analysis. Data quality issues discovered during post-analysis included: -

(i) Stability of nvPM data - to perform comparisons the data needed to be stable. If the nvPM reading was not stable (within 10% over a 2 minute period) during a steady engine condition it was removed. Such a data point would thus appear blank in the merged spreadsheet (Table 1).

(ii) It was observed that the measured CO_2 (%) on one test was low and indicated a leak in the line or equipment and this same leak was indicated by other gaseous species measurements. This produced an action to provide a positive time of test feedback to confirm the CO_2 measured would agree with the exit AFR from the engine under test. The faulty readings were replaced by CO_2 values from curve fitting with other similar engine data.

(iii) One dataset of ambient conditions were clearly incorrect (1000˚C), therefore ambient conditions from the local airport weather station were used as a substitute.

(iv) Further data quality checking involved considering the Smoke Number and first order approximation to see if the non-volatile mass concentration measured were in agreement. Then comparisons between the ICAO emissions databank engine data sheet gaseous and smoke values to the measured values were also checked (noting that the engine probe was a fixed single point probe). It has to be noted that for the need to maintain proprietary data, the measured gaseous emissions data are not included in this report.

5.2.1 Data Analysis

During the SAMPLEIII SC02 measurement campaign the primary objective was to achieve comparison of two SAE E31 compliant sampling and measurement systems to give confidence in the proposed methodology. However, a number of other objectives were also assessed, such that over the 2 week campaign period the sampling and measurement system setup slightly changed between specific engine tests (dedicated and piggyback types). This meant that a consistent nvPM dataset using the diluted SAE E31 concept was not available across all engine tests. However, in order to assess the sampling system penetration during the campaign, a DMS500 and an LII300 were positioned on the gantry inside the SR Technics engine test cell. The instruments sampled from the same splitter used to separate the undiluted sample flow from the probe to both the SAMPLEIII and FOCA/Swiss dilution boxes.

The gantry DMS500 was a consistent measure of PM throughout the measurement campaign and could therefore be used to assess engine PM signature variability. Though there was no VPR upstream of the DMS, the in-built heated (160°C) dilution system helped to prevent organic/volatile aerosol formation, based on current scientific understanding that organic carbon does not form homogeneous nucleation at levels found in gas turbine exhaust. For the purpose of this analysis the data output from the DMS is assumed to be nvPM.

It is expected that the DMS measured results would be a little higher than those measured by other instruments downstream of the diluted sampling system owing to the extra diffusion particle loss mechanism associated with the extra (24m) line length from the point of dilution to the instruments.

To convert the DMS data to a mass concentration, a density function was used that is in-built to the instrument software (based upon a miniCast particle source, carbon density is described as a function of particle size). Though mass concentration measurement comparisons with size distribution-derived data often show good correlation, the absolute numbers should be used qualitatively rather than quantitatively. In addition as there are assumptions about the particle density and charging correction (as with all electrical mobility-based particle size instruments) and the fact this piece of equipment is not described in AIR6241, the data quality level means future comparison with other compliant instrument results would need to be done with care. That said the purpose of this exercise was to consider effects of ambient temperatures as well as engine to engine variation, and as the DMS instrument was operating consistently at the same sampling location (including passing instrument checks such as zero noise) throughout the entire campaign this comparison data is still appropriate.

As stated previously the task helped develop analysis techniques that can be found in the current AIR6241 and provided some first considerations detailing how effective data averaging and stability checks could potentially be performed.

The resultant values are presented in Table 1 below, it should be noted that due to confidentiality issues many proprietary parameters have been removed, but this table provides the source of the data for the subsequent plots, which illustrate ambient effects and engine-to-engine variations of the engines tested.

Table 1 Data Obtained and Analysed from DMS Funded by SAMPLE III.SC02 Programme

Engine Type	Date 2012	Comb. Type	Emissions Data ID	100% Thrust kN	Test bed	Thrust kN	Thrust % of TO	T_{amb} °C	P_{amb} PSI	RH %	Dew point °C	DMS Data		Emissions Index	
												Mass μ/m³	N° #/cm³	N° #/kg	Mass μ/kg
CFM56-7B26	25/4	SAC	8CM051	117	Zurich	41.0	35.0	22.8	13.9	21.4	-0.5	90	5.4E+06	2.9E+14	0.005
						74.1	63.3	22.8	13.9	21.3	-0.4	255	5.7E+06	2.4E+14	0.011
						94.6	80.9	22.7	13.9	21.4	-0.4	903	1.1E+07	4.2E+14	0.034
						118.1	101.0	22.8	13.9	21.3	-0.4	1523	1.2E+07	4.2E+14	0.052
						3.5	3.0	22.9	13.9	21.3	-0.3	0	3.2E+06	7.0E+14	
						8.4	7.2	23.1	13.9	21.0	-0.3	6	4.0E+05	6.2E+13	0.001
						3.5	3.0	23.2	13.9	21.0	-0.3	35	*3.5E+06*	7.7E+14	0.008
CFM56-7B26/3	23/4	SAC Tech Insert	8CM065	117	Zurich	41.6	35.6	7.7	13.9	79.8	4.2	43	3.2E+06	1.8E+14	0.002
						75.0	64.1	7.7	13.9	80.1	4.2	406	1.3E+07	5.9E+14	0.018
						95.6	81.7	7.7	13.9	79.3	4.1	763	1.5E+07	6.1E+14	0.030
						119.4	102.1	7.6	13.9	80.2	4.1	1255	1.5E+07	5.2E+14	0.044
						3.6	3.1	7.6	13.9	81.4	4.3	238	2.1E+07	1.5E+15	0.017
						7.8	6.7	7.5	13.9	82.1	4.4	82	1.9E+06	1.4E+14	0.006
						3.5	3.0	7.5	13.9	81.5	4.3	194	1.6E+07	1.2E+15	0.014
CFM56-7B26/3	31/4	SAC Tech Insert	8CM065	117	Zurich	3.2	2.7	16.0	14.0	16.6	-8.4	150	1.1E+07	1.0E+15	0.013
						40.7	34.8	16.0	14.0	16.3	-8.6	309	1.2E+07		
						73.8	63.1	16.0	14.0	16.2	-8.6	275	1.0E+07	4.4E+14	0.012
						93.8	80.1	15.0	14.0	16.1	-9.5	699	1.5E+07	6.4E+14	0.028
						103.8	88.8	15.0	14.0	16.0	-9.6	1097	1.3E+07	4.9E+14	0.042
						118.0	100.8	15.0	14.0	16.0	-9.6	1304	1.1E+07	4.1E+14	0.048
						3.1	2.7	15.0	14.0	16.2	-9.4	157	6.4E+06	5.7E+14	0.014
CFM56-5B4/2P	28/4	DAC	3CM021	120.1	Zurich	8.3	6.9	28.8	13.9	12.0	-2.8	76	3.1E+07	2.3E+15	0.006
						12.3	10.2	28.9	13.9	11.8	-3.0	71	4.6E+07	3.2E+15	0.005
						16.9	14.0	28.8	13.9	11.8	-3.1	78	6.1E+07	4.0E+15	0.005
						26.2	21.8	29.0	13.9	11.8	-2.9	73	9.3E+07	5.4E+15	0.004
						33.7	28.1	28.9	13.9	12.0	-2.8	1056	4.8E+06	3.0E+14	0.066
						34.1	28.4	28.9	13.9	11.6	-3.1	426	4.8E+06	3.0E+14	0.027
						26.1	21.7	29.1	13.9	11.2	-3.4	181	8.4E+07	5.3E+15	0.011
						16.4	13.7	29.0	13.9	11.7	-3.0	603	5.2E+07	3.8E+15	0.044
						7.9	6.6	29.1	13.9	11.4	-3.2	1708	3.2E+07	2.7E+15	0.146
						4.4	3.6	28.9	13.9	11.0	-3.7	3644	2.0E+07	1.7E+15	0.314
						10.3	8.6	28.5	13.9	11.8	-3.2	107	3.9E+07	3.2E+15	0.009
						19.7	16.4	28.2	13.9	11.5	-3.7	228	6.7E+07	4.8E+15	0.016
						29.1	24.3	28.0	13.9	11.9	-3.5	623	9.5E+07	6.1E+15	0.040
						34.2	28.5	28.0	13.9	11.3	-4.0	1704	5.1E+06	3.6E+14	0.118
						4.3	3.6	27.5	13.9	12.1	-3.6	3889	1.7E+07	1.6E+15	0.362
						10.8	9.0	27.1	13.9	13.0	-3.0	67	4.0E+07	3.5E+15	0.006
						20.3	16.9	27.0	13.9	12.7	-3.4	163	6.9E+07	5.0E+15	0.012
						30.0	25.0	26.5	13.9	13.9	-2.7	0	9.8E+07	6.5E+15	
						35.2	29.3	26.5	13.9	13.6	-3.0	0	5.0E+06	3.6E+14	
CFM56-5B4/2P	29/4	DAC	3CM021	120.1	Zurich	12.1	10.1	22.4	13.9	37.6	6.2	796	4.2E+07	3.4E+15	0.064
						22.4	18.7	22.1	13.9	41.0	7.0	2619	8.4E+07	6.8E+15	0.210
						32.9	27.4	21.9	13.9	41.7	7.1	4993	1.1E+08	7.5E+15	0.344
						37.6	31.3	22.7	13.9	35.1	5.6	98	5.6E+06	5.0E+14	0.009
						112.7	93.9	23.2	13.9	34.9	5.8	25	7.1E+05	4.1E+13	0.001
						124.0	103.2	22.8	13.9	34.5	5.4	19	3.6E+05	1.5E+13	0.001
CFM56-5B4/2P	30/4	DAC	3CM021	120.1	Zurich	22.1	18.4	17.8	14.0	52.3	6.9	2247	7.3E+07	5.4E+15	0.168
						27.6	22.9	18.3	13.9	50.3	6.8	3652	8.8E+07	6.9E+15	0.287
						31.1	25.9	19.0	13.9	46.7	6.4	4402	1.0E+08	8.2E+15	0.361
						39.3	32.7	20.2	13.9	41.5	5.8	94	5.7E+06	5.6E+14	0.009
CFM56-5B3P	29/4	SAC	3CM025	142.4	Zurich	42.3	29.7	9.3	13.8	74.5	4.7	81	4.2E+06	2.3E+14	0.005
						78.5	55.2	8.6	13.8	77.0	4.5	677	1.3E+07	5.5E+14	0.028
						101.1	71.0	8.8	13.8	77.2	4.7	779	1.2E+07	4.4E+14	0.029
						122.3	85.9	9.3	13.8	74.9	4.7	1152	1.2E+07	4.1E+14	0.039
						3.6	2.5	9.6	13.8	69.7	4.0	40	3.3E+06	3.3E+14	0.004
						7.7	5.4	9.7	13.8	69.4	4.1	28	1.8E+06	1.7E+14	0.003
						3.6	2.5	9.9	13.8	66.4	3.6	80	3.7E+06	4.2E+14	0.009
CFM56-5C4 mixed exhaust	26/4	SAC	2CM015	151.3	Zurich	4.3	2.8	16.4	14.0	53.6	6.2	49	5.0E+06	1.7E+15	0.017
						49.4	32.6	16.7	14.0	52.8	6.2	25	1.9E+06	4.3E+14	0.006
						87.8	58.0	16.6	14.0	52.1	5.9	140	2.8E+06	5.7E+14	0.029
						112.8	74.6	16.8	14.0	51.7	6.0	246	3.0E+06	5.9E+14	0.049
						127.8	84.5	16.9	14.0	50.5	5.8	356	4.5E+06	8.5E+14	0.067
						8.9	5.9	17.1	14.0	49.3	5.6	20	8.5E+05	2.8E+14	0.007
						4.3	2.9	17.5	14.0	45.2	4.9	24	2.6E+06	9.0E+14	0.008
PW4462-3	25/4	SAC	1PW059	275.8	Zurich	11.9	4.3	15.8	14.0	45.6	3.6	129	7.8E+06	8.5E+14	0.014
						270.7	98.2	16.7	14.0	45.3	4.2	3063	2.5E+07	9.8E+14	0.121
						21.2	7.7	15.7	14.0	45.5	3.6	25	1.7E+06	1.8E+14	0.003

A brief explanation of Table 1 is given as follows:

- The first 6 columns give limited information which identify the engine type and particular combustion system and include the ICAO emissions databank ID.
- The ICAO databank 100% thrust number is given in column 5 which was used to normalise the thrust, for the plots presented below.
- Column 7 includes the thrust directly from the test bed, corrected for ambient conditions and test cell effects. It is noted that this will not necessarily be comparable to the ICAO datasheet thrust, but as it is a consistent measurement throughout all testing, it offers a reliable method to compare data (column 8 gives the % of the 100% thrust of the test point).
- The next several columns give the ambient conditions including the temperature, pressure and humidity. It should be noted that humidity is a factor necessary for correcting NOx emissions and may or may not be important for nvPM emissions.

The DMS concentration results shown are averaged over a suitable time period (for this testing this was typically >2 minutes) with the engine on a steady condition. The averaged concentrations are then converted to an Emissions Index (EI) by using the measured CO_2 over the same time period. The EI values in practice could have been plotted against many parameters and potentially in the future such plots may be done by engine manufacturers using proprietary data such as T30, but for the purpose of comparing the results they were plotted against % thrust level. The results are presented in the section below.

5.2.2 Results

The measurements of nvPM mass agreed with the smoke number measurement via the FOA3 correlation and it is observed that there are data sets for engines additional to those used for comparisons presented here. However, this additional dataset may be useful as comparative data in the future if engines of these types are tested. The DAC engine was run over 3 dedicated days to help the development of the AIR and to finalise the measurement techniques to be used. The results from these 3 days are shown in Figure 3 below.

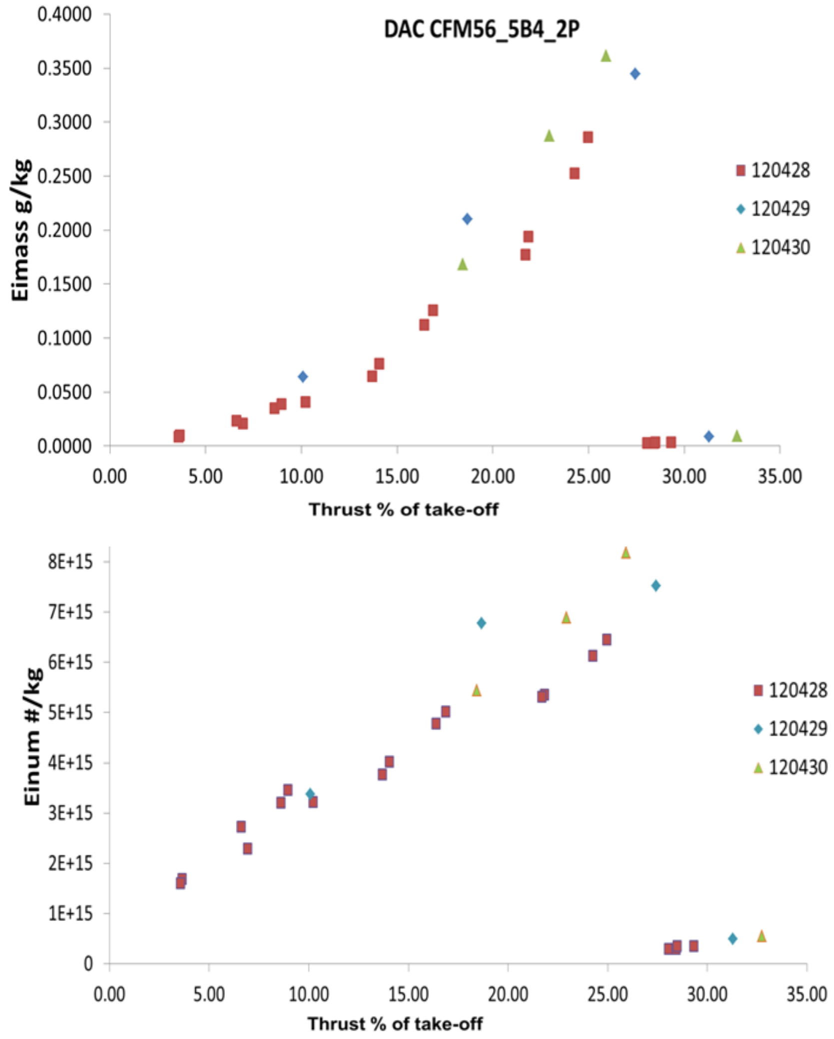


Figure 3 (a&b) EI nvPM DMS Mass and Number Data respectively from CFM56 DAC Engine, single point probe, SAMPLE III.SC02 28th, 29th & 30th April 2012

The red squares shown give results measured on the 28th April 2012 with 26.5-29°C ambient temperature and around 12% humidity. The blue diamond's shown give results measured on the 29th April 2012 with 22-23°C ambient temperature and around 37% humidity, and the green triangles shown give results measured on the 30th April 2012 with 18-20°C ambient temperature and around 47% humidity. The data in Figure 3a suggests repeatability of 20% or better although there appears to be some evidence there is less nvPM on hotter days. There is no evidence of an effect of humidity noting that it may be best to consider absolute humidity if this effect is looked at in more detail in the future.

The EI nvPM number versus thrust plot shows very similar trends with potentially slightly more scatter. As the range in day temperatures during this campaign was only 11°C which is relatively small, more data is needed across a larger range, in order to truly understand the effect of ambient temperature, however, the data repeatability seems reasonable and within expected limits.

The next comparison considered is that of one particular engine type, with 3 physically different engines being sampled during the test campaign in spring 2012. Two of these engines had the newer low NOx emissions combustor with the other utilising an older combustor technology, however on consultation of the emissions databank sheet it was observed that there is little difference between the quoted smoke numbers, between these two combustor variants thus all 3 engines are compared in order to enhance the dataset.

Unfortunately, these 3 engines were tested on different dates and hence at varying ambient conditions therefore the data presented for these engines given in Figure 4 below, include both engine to engine variation superimposed on ambient temperature variations.

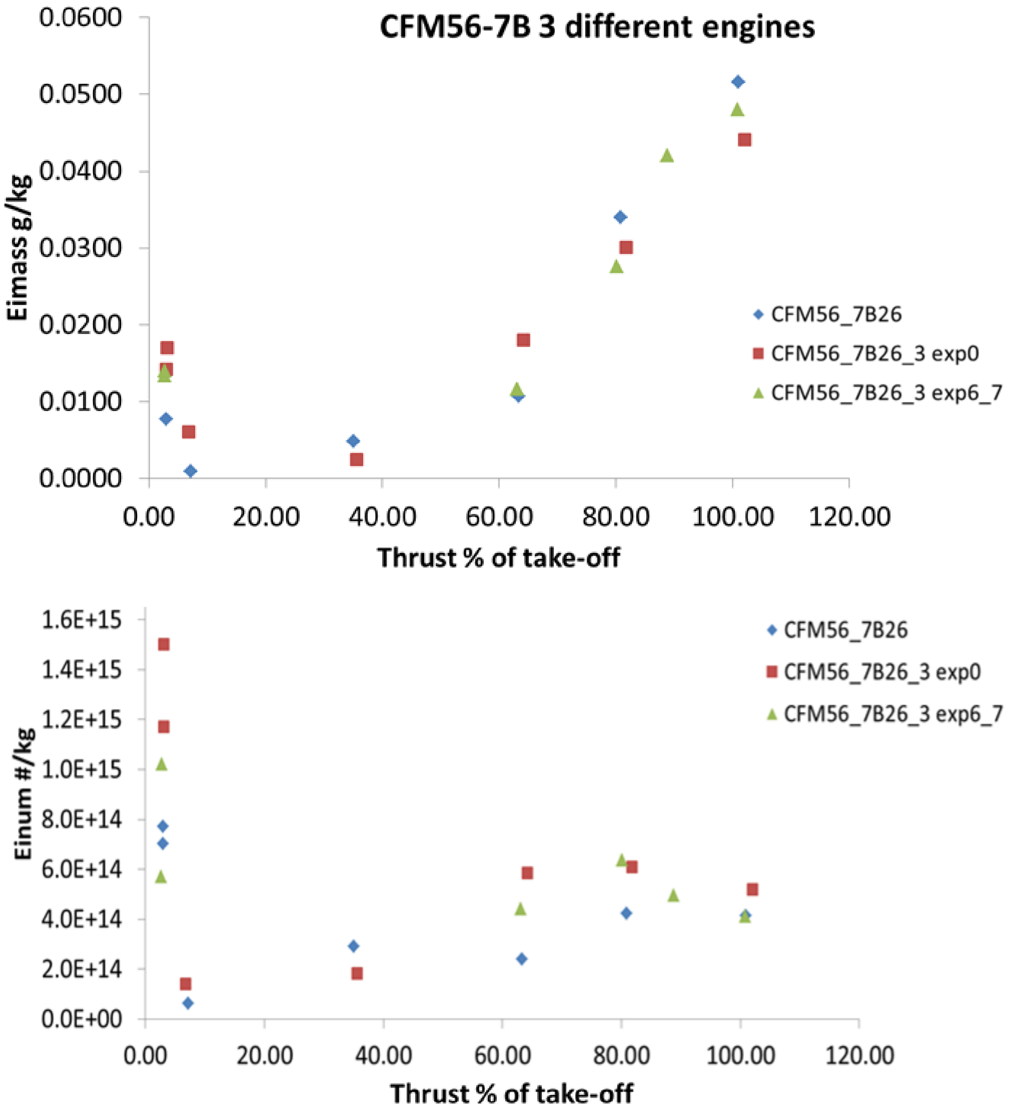


Figure 4 (a&b) EI non volatile PM Mass and Number DMS Data respectively from CFM56 SAC Engine, single point probe, SAMPLE III.SC02, April 2012

Once again Figure 4a shows excellent repeatability between all 3 engines with lowest mass measured at approach power conditions and increases below and above this point at idle, and at a maximum at the highest thrust levels, witnessed at take off like condition.

The blue diamond's shown in Figure 4 give results measured on a day with ambient temperatures of approximately 23^{o}C and 21% humidity, the red squares were measured at ambient values of 8°C temperature and 80% humidity, and the green triangles measured on a day with ambient temperature 15.5°C and 16% humidity. Thus for this comparison the range of temperatures is 15°C with temperatures above and below ISA (ICAO Standard Atmosphere) day temperature. It is again observed that there is excellent repeatability in the results of 20% or better in the EI PM mass data. However, it should be noted that more scatter is witnessed in the number measurement (Figure 4b) especially at idle, but overall there is little difference in the variability displayed in this engine to engine dataset compared to that observed in the aforementioned dataset utilising the same DAC engine tested on different days (Figure 3).

These two datasets thus raise the question as to whether corrections are required for differences in combustor inlet conditions. However, care must be taken in assuming this theory as it may be that conflicting effects on hot and cold days, are masked by opposite trends brought about by engine variability, as such this is investigated further in the following sections.

5.3 SAMPLE & SAMPLE II Engine Variability Data

So that a better understanding of PM variability may be sought, data that can be used to further analyse engine to engine variations and other effects of ambient conditions taken during the SAMPLEIII SC02 test campaign is compared to data from other SAMPLE test campaigns. During SAMPLE I and SAMPLE II two Trent engines of the same type were tested. In SAMPLE I the sample was diluted close to the instruments and there was no VPR, whereas in SAMPLE II it was diluted near the probe and this is noticeable on the number measurements (higher numbers on the diluted line due to coagulation being prevented, but higher numbers at low power for SAMPLE I where there was no VPR). Figure 5a shows data for these Trent engines that agrees with the 2012 test campaign in that lower variations are again observed for PM mass compared to number, however, differences of around 50% are witnessed in this comparison, higher than the 20% observed when a consistent sampling system was employed. Again the observed PM number variation (Figure 5b) is larger, but as discussed previously the different dilution positions and sampling systems are likely contributing to this additional variation. The engine power is proprietary but the scale is a representative engine power parameter.

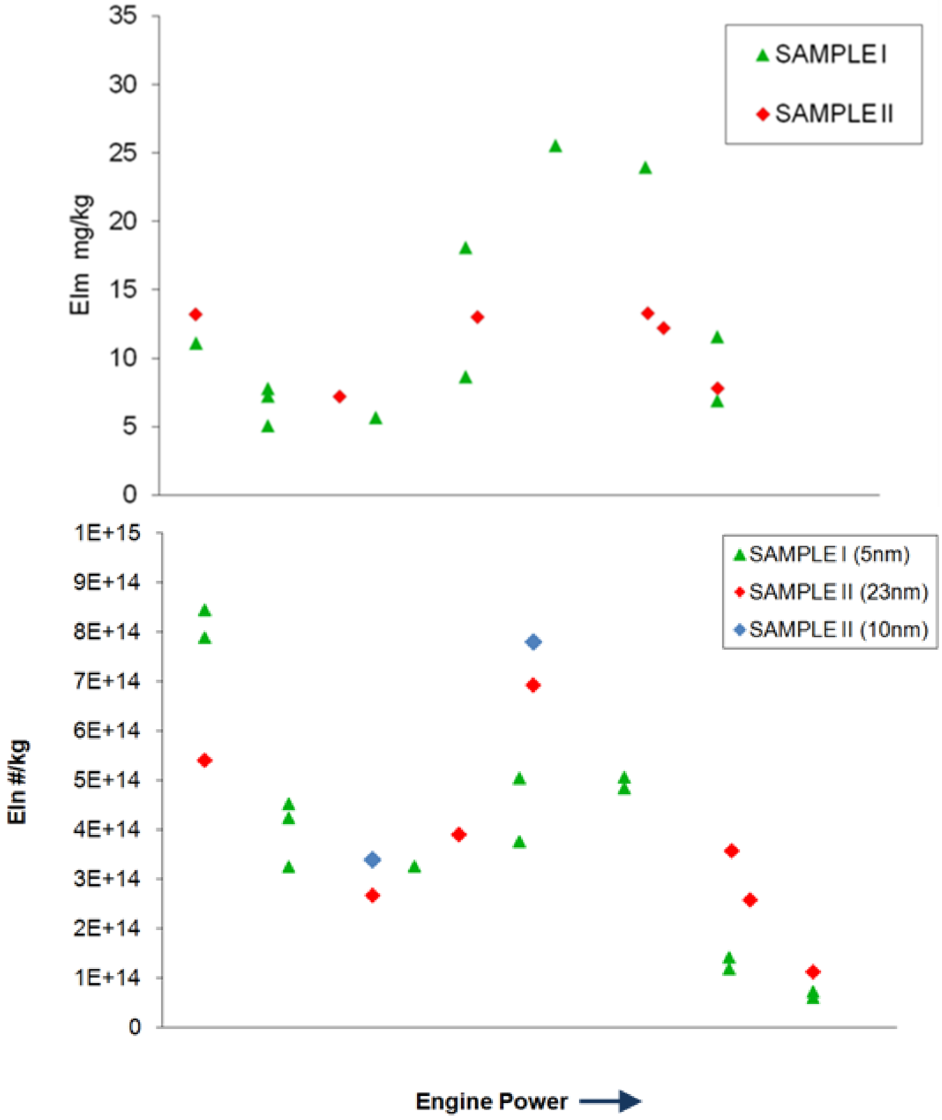


Figure 5 (a&b) EI non-volatile PM mass and number from two same-type Trent engines with different sampling systems performed during SAMPLE I & SAMPLE II. The particle sizes in the EIn legend represent the D50 cut point of the CPC used to obtain the number measurement

The day temperatures on these two tests were fairly similar with the SAMPLE I results taken at typically 12^{o}C and humidity 60-80% and the SAMPLE II results at 6^{o}C 80-90% humidity.

The testing reported later in detail for Task 3b of this body of work (SAMPLE III SC03) conducted at Zurich during August 2013 also used a dedicated CFM56 SAC engine, with testing conducted on a variety of different days, typically with temperatures witnessed on hot summer days. However, during this test campaign a compliant, consistent sampling and measurement system were employed throughout which potentially offers a more robust comparative dataset, which is discussed briefly later in section 7.3.6 with the original EI number and mass data given in Figure 75. As such this data is presented to help provide recommendations on how to better perform future engine variability studies.

Once again plotting the data against reported thrust (FNK2) showed a reasonable comparison of results (Figure 6) for mass and number, across ambient conditions varying from 18ºC to over 30ºC.

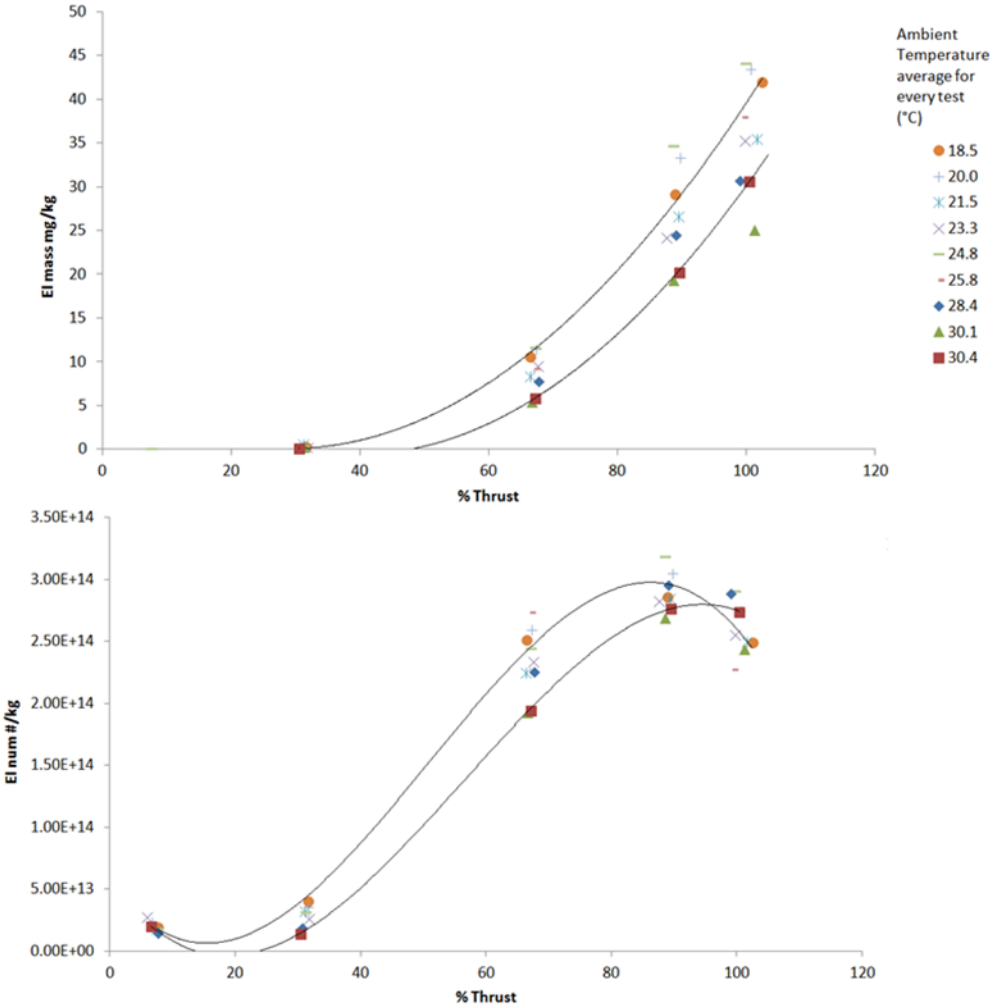


Figure 6(a&b) Ambient Condition effects on EI non-volatile PM Mass & Number from CFM56-7B26/3 (SAC) SAMPLE III.SC03 August 2013, plotted against test bed measured thrust. Curves are fitted on the highest and lowest ambient temperature data, 2nd order for mass and 3rd order for number.

For the engine data gathered during SC03 Task3b, the T30 engine parameter (and other useful performance parameters) was not made available to this report's authors due to proprietary concerns. Therefore the Swiss FOCA applied a correction method to the measurements and provided a thrust corrected T30 that reflects the different ambient conditions.

When this FOCA thrust correction is applied to the data then the data collapses very nicely onto one curve (Figure 7). This may be indicative that using T30 rather than thrust will automatically take into account different ambient conditions that are encountered during testing on non-ISA days, but clearly more work is needed to confirm this hypothesis and to understand the additional uncertainty of engine to engine variability, discussed earlier.

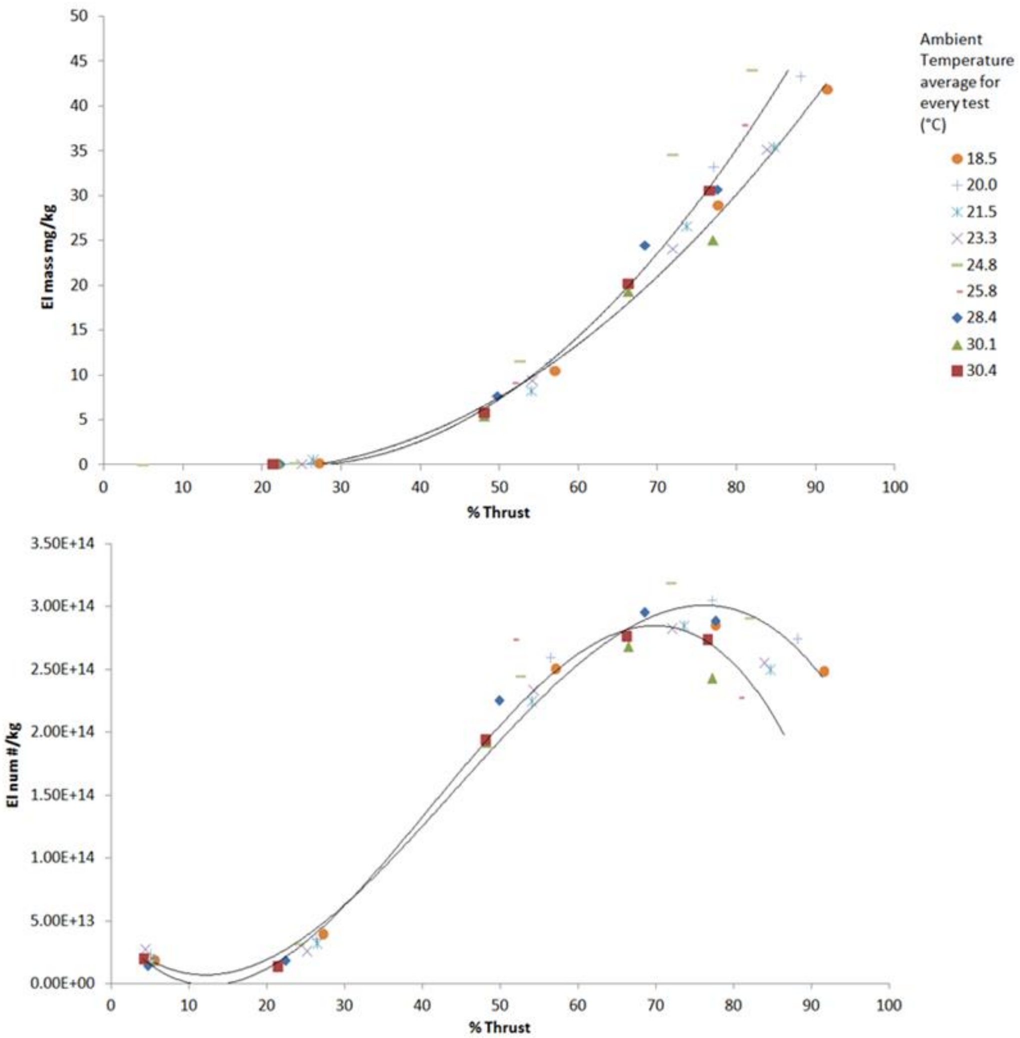


Figure 7 (a&b) Ambient Condition effects on EI non-volatile PM Mass & Number from CFM56-7B26/3 (SAC) SAMPLE III.SC03 August 2013, Plotted against T3 Corrected Thrust. Curves are fitted on the highest and lowest ambient temperature data, 2nd order for mass and 3rd order for number.

5.4 Discussion

A possible explanation for change or lack of change of engine nvPM resulting from ambient changes is discussed below.

As ambient temperature increases typically an engine is less efficient, owing to the fact that compression of air is more difficult. Thus to generate the required thrust more fuel is needed resulting in a richer fuel to air ratio (FAR), but due to the compression inefficiency the P30 (Combustor inlet pressure) at a T30 (Combustor inlet temperature) is lower. However, the effect of lower P30 at a T30 and thrust is a net reduction in nvPM; in contrast an increase in nvPM would be expected at higher fuel flows and richer fuel to air ratios at a T30 and a thrust. These phenomena will thus reverse when the ambient temperature decreases.

As such these two counterbalancing effects may need to be considered independently to allow for ambient correction., and the effects may counteract each other in such a way that corrections for ambient conditions are not required if a corrected T30 is adopted. However, not withstanding this explanation of ambient effect engine to engine variability, still needs to be assessed independently so that true variability can be determined and ICAO can decide whether both subjects may be considered together.

To date, engine-to-engine variability of the same engine type has been proven to be within the expected variation (20% for mass and 30-40% for number), when sampled and measured using consistent methodologies. Given the fact that engines have been tested at a variety of ambient conditions, this may suggest that engine to engine PM variability is actually smaller than the measurement uncertainty. It should be noted, as discussed earlier, engine-to-engine variability may or may not encompass variations in ambient conditions, which may counteract each other during this limited dataset, thus care should be expressed when interpreting the lack of variability.

On inspection of some of this data there is limited evidence that higher ambient temperatures may bring about a reduction of nvPM and so far no effect of relative humidity is necessarily observed. The authors wish to express that caution should be applied and that the findings of this limited study are not necessarily applicable to all engine types.

Hypothetically, it is understood that water in the combustion system brings about a net reduction of smoke emissions from industrial gas turbines. Other engine testing has demonstrated this fact if water is injected with the fuel. However, if water is injected at other combustion locations it depends on whether the reaction is quenched or is well mixed as to the observed result. In the case of addition of water to the inlet air, as would be the case of increased humidity, then it may be expected that a net reduction in nvPM should be observed, However as stated earlier there is no evidence in this dataset from engine testing to date of the effects of ambient humidity altering observed nvPM.

In the future, additional data is required to see if corrections are required for ambient conditions or not, noting the conflicting effects on nvPM production of varying ambient temperature, due to FAR and P30 effects. The authors offer that combustion rig testing may be utilised so as these effects could be considered independently.

Consideration is required on the expectations for engine to engine variability coupled with ambient condition effects. As an example the characteristic correction for one engine test on smoke is 28% (1/0.7791) so greater than the expected measurement uncertainty of 20% for nvPM mass. As such funding bodies will need to support more testing at different ambient conditions, with additional engine to engine variability comparisons. In addition the measurement uncertainty for EInvPM needs to be quantified allowing an assessment of whether PM variability is engine or measurement system based.

5.5 Conclusions of Task 2

1. Data from SAMPLEIII SC02, suggests a repeatability of 20% or better for nvPM mass and 30-40% for nvPM number if considering repeats on a particular engine.
2. Thrust levels can be used to consider total nvPM variability on repeated engine data, however, it is likely that engine manufacturer proprietary parameters (such as T30) will need to be plotted to fully assess nvPM engine variability.
3. Analysis of existing data indicates that it is not obvious, due to conflicting combustion physical processes (related to combustor inlet Temperature and Pressure), whether

ambient corrections are required for nvPM. There is some limited evidence that elevated ambient temperature may reduce PM.

4. Engine-to-engine variability data may or may not encompass variations in ambient conditions
5. Combustion rig testing (with AIR6241 instrumentation) is likely required to consider the effects of Fuel-Air-Ratio (FAR) and P30 (inlet combustor pressure) independently
6. Consideration of variability expectations for engine-to-engine need to be considered by regulators and funding bodies, in order that regulated values including statistical compliance can be adopted.

1. More engine testing is required with AIR6241 sampling/measurement systems to assess engine-to-engine variability.

6. Task 3a: Design and Manufacture of EU/EASA Mobile Reference System

6.1 Introduction

In order to be compliant with current SAE E31 nvPM sampling methodology the mobile reference system was built in compliance to AIR 6241. However, as this system was to be the EU/EASA mobile reference system there were additional specifications which were adhered to in accordance with the recommendations of the SAE E31 as agreed at the PM subcommittee meeting (Zurich, January 2013).

To conform to the aforementioned recommendations, two mass instrument types, namely the AVL MSS and Artium LII (one serial number fixed to the system) were designed into the system as discussed further in Section 6.3.7.

6.2 Mobile reference system overview

As discussed the mobile reference system was built in compliance with AIR 6241 which lays out the sampling system equipment systematically and schematically in Figure 8 & Figure 9 respectively. Note that PTS = Particle Transfer System, GTS = Gas Transfer System.

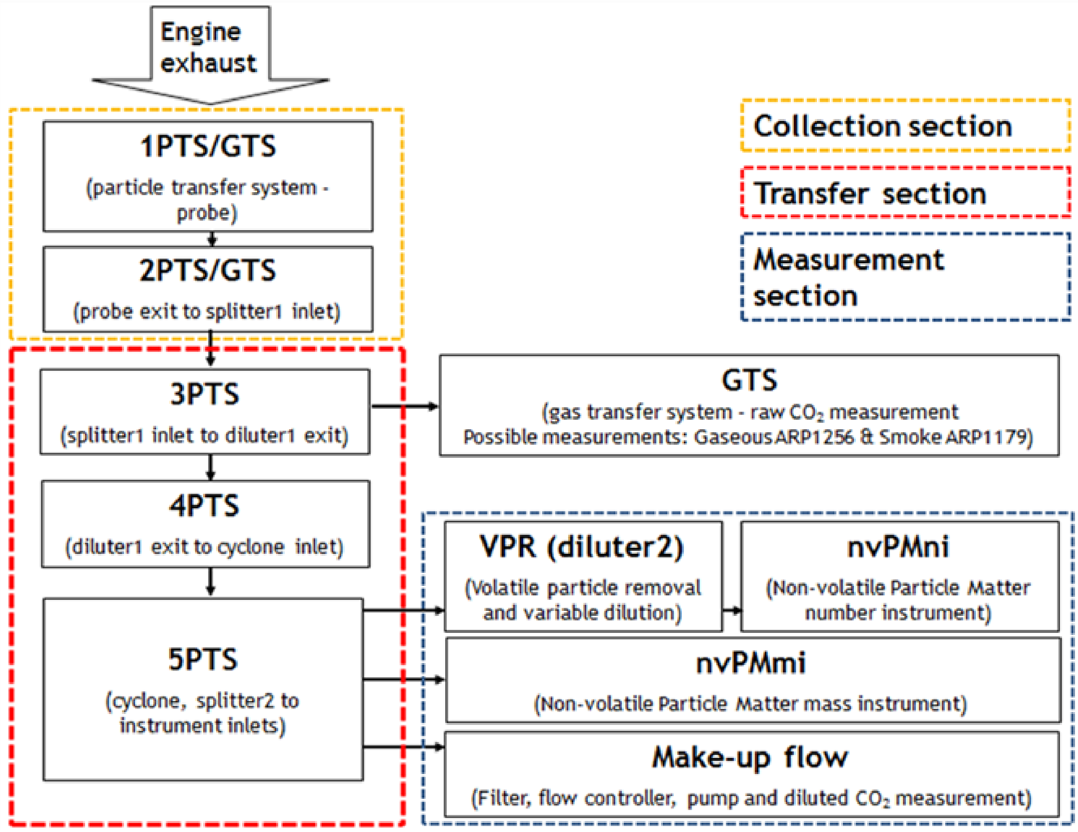


Figure 8 AIR 6241 Non volatile PM measurement system flowchart

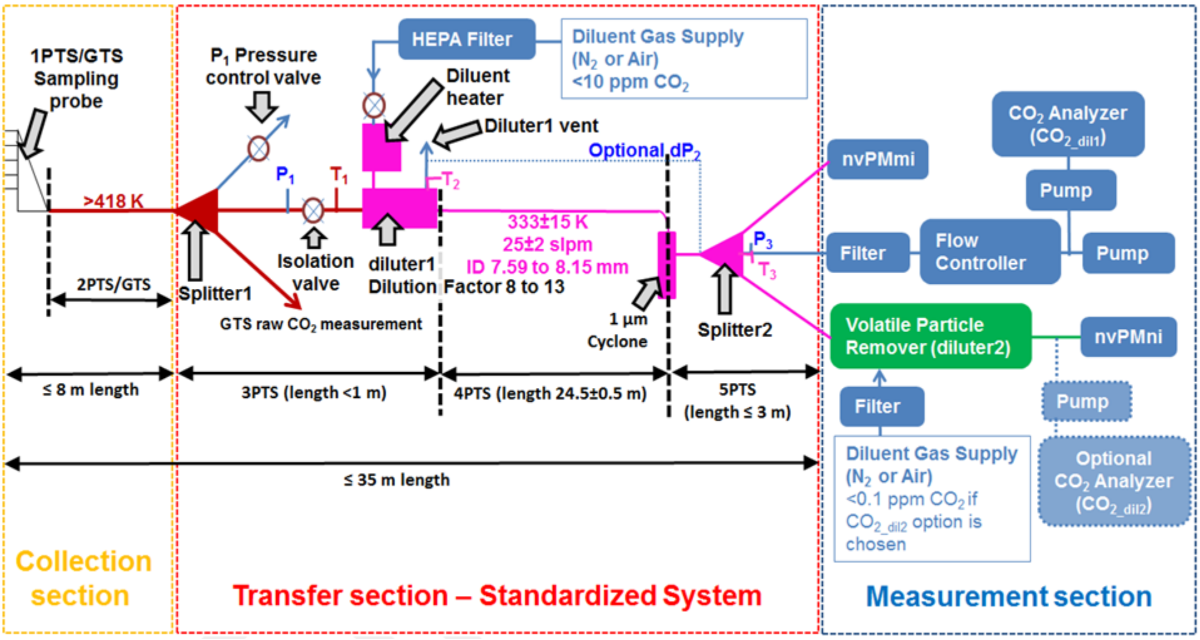


Figure 9 AIR 6241 Schematic of non volatile PM system

As can be seen AIR 6241 compliant systems are thus broken into three distinct sections namely the collection, transfer and measurement sections with further details of how to construct and operate each section given in the report.

Further detail of the EU/EASA reference systems components is given below in Section 6.3, and a summary of conformance in Section 6.5.

6.3 Mobile reference system components

As discussed the EU/EASA mobile reference system was constructed to be in compliance with both AIR 6241 in addition with suggestions laid out by the SAE E31 PM subcommittee for reference systems. As such each section highlighted in Figure 9 along with the additional requirements for a mobile reference system was designed with details of each given below.

6.3.1 Particle Transfer System (1PTS)

This section of the system is specific to the engine type and thus is not part of the EU/EASA reference system. As such details of this section will be discussed in the relevant experimental setup sections of the data chapters.

6.3.2 Probe Exit to Splitter 1 (2PTS)

Again this section of the sampling system is specific to the engine and test campaign, specific details will be discussed in the experimental setup sections of the data chapters. However, as described below in section 6.3.3, the EU/EASA mobile reference system does contain a 2m flexible heated line which could be installed solely as 2PTS if 2PTSa is not required (i.e. if AIR6241 system comparison test is not required).

6.3.3 Additional Splitter and heated lines (2PTSa)

To operate the EU/EASA mobile reference system in a comparative test with the other reference systems it was necessary to add an additional splitter (upstream of Splitter 1) and sample line (2PTSa) into the suggested AIR 6241 compliant nvPM sampling system as shown in Figure 10.

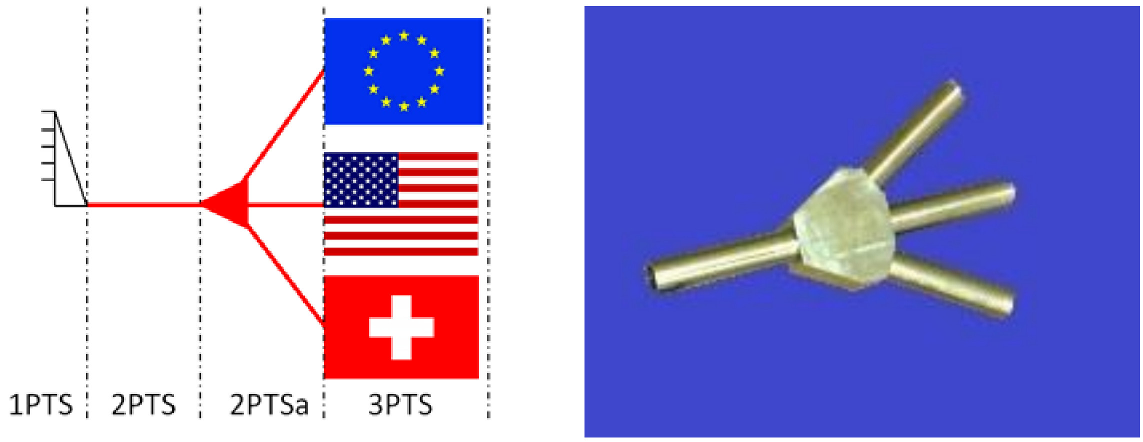


Figure 10 (a&b) Schematic representation and photograph of additional sampling section splitter (2PTSa) respectively

In order to facilitate both two and three way inter-comparisons it is necessary to utilise a 3 way 10mm OD (8mm ID) splitter with 30° angle, which was purpose built to the AIR 6241 specifications by the SAMPLE III consortium.

As shown in Figure 10(a) to connect the splitter to multiple systems additional sample lines are required. In order to make the reference system as versatile as possible it was decided that two additional 2m heated lines conforming to the specifications of material and line diameter for section 4PTS in AIR 6241 would be manufactured. Full details of their construction are given in Section 6.3.5 and therefore will not be discussed further at this time.

6.3.4 Primary Splitter & Diluter Box (3PTS)

The primary splitter (Splitter 1) and diluter box is a development of the hardware used and described in previous test campaigns (SAMPLE III SC02 http://www.easa.europa.eu/safety-and-research/research-projects/environment.php). In order to ensure compliance with the new AIR 6241 specifications, it was necessary to modify some of the internal geometries and control instrumentation locations, along with the addition of the remote (automatic) operation of the spill line isolation valve (labelled V3 in Figure 12). Photographs and schematic representations of the SAMPLE III primary splitter and dilution box are given in Figure 11 & Figure 12 respectively. It should be noted that additional thermocouples (further to those required in AIR6241) were installed in the dilution box to help provide more system diagnostic information.

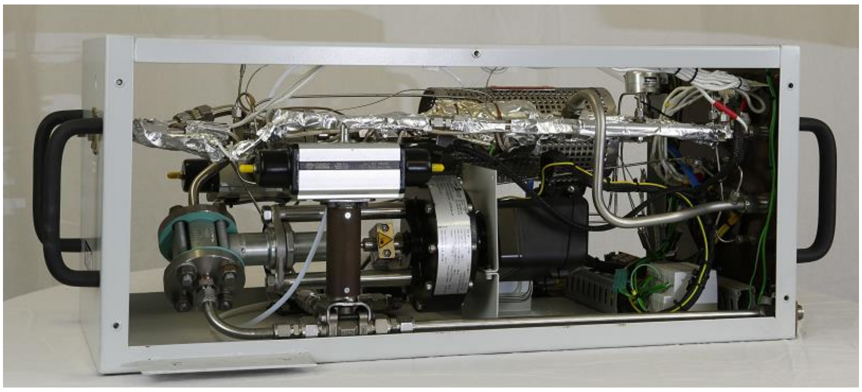


Figure 11 Internal photograph of SAMPLE III primary splitter and diluter box (3PTS)

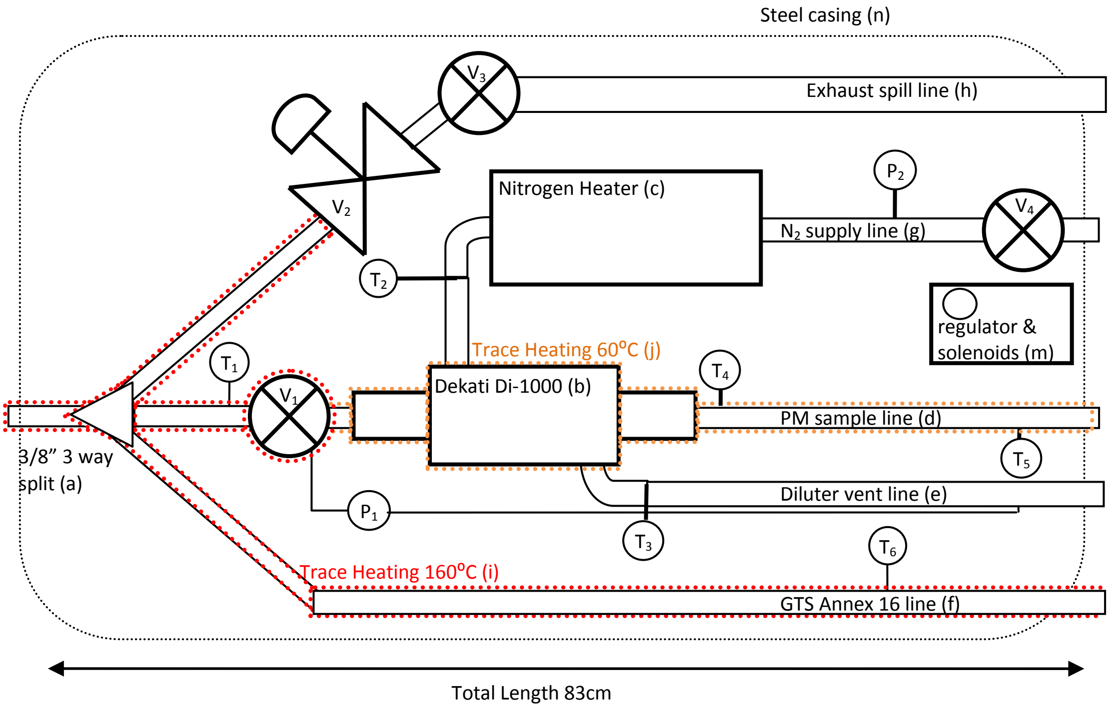


Figure 12 Schematic representation of SAMPLE III primary splitter and diluter box (3PTS)

6.3.5 Heated Carbon Loaded PTFE Sample Line (4PTS)

New AIR6241 compliant sample lines were constructed using specially sourced carbon loaded (anti static) PTFE tubing which was braided with a stainless steel outer sheath. This tubing was then manufactured into heated lines as shown in Figure 13. Unlike trace heated sampling lines, the lines produced for this study use an induced current in the stainless steel braid to act as the heating element, this is achieved by connecting the braided tube in series with a relevantly specified voltage transformer. Because the braid is uniformly wrapped around the entire tube it is thought that a better uniform heating is applied to the entire outer wall of the heated line using this method rather than the trace heating methodology used in other commercially available sample lines. Because the voltage applied is calculated for the length of the line, the maximum temperature that can be achieved is self regulating and lower than the upper temperature limit of PTFE which acts as a failsafe should the temperature controller fail.

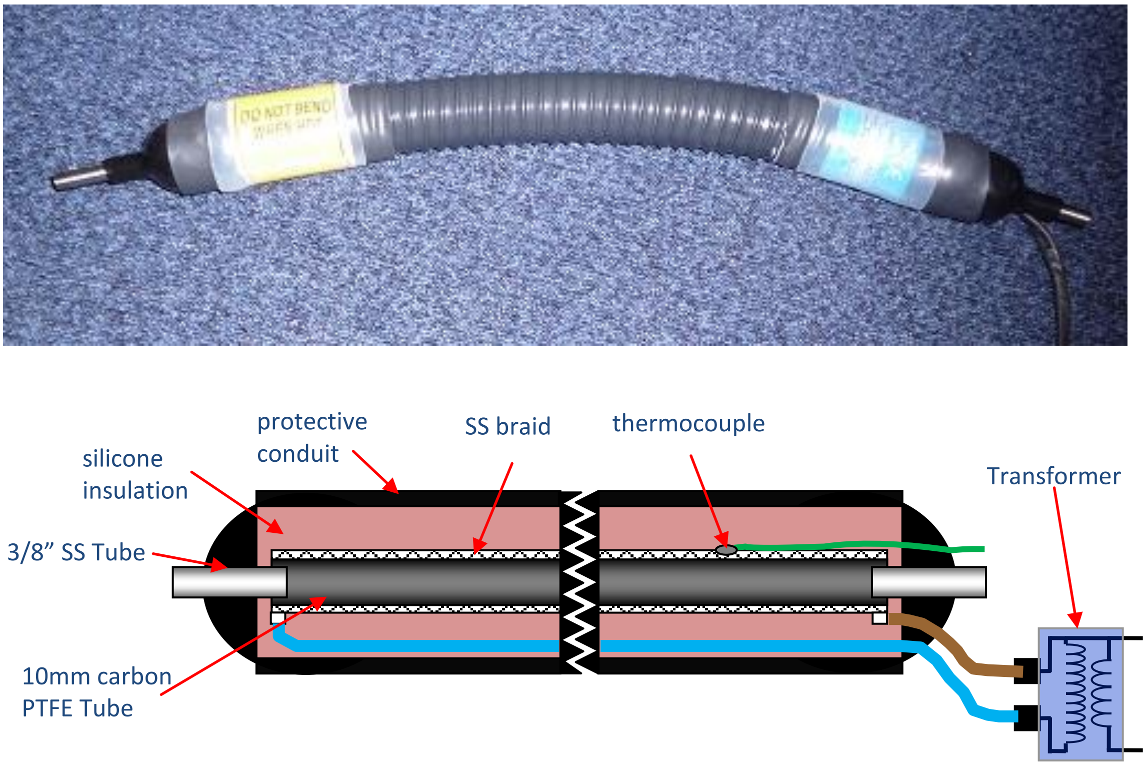


Figure 13 Photograph and Schematic representation of Signal Instruments Carbon loaded PTFE heated lines used in EU/EASA mobile reference system

Three thermocouples are also positioned along the length of the line in contact with the braid for use for temperature control and to ensure that the line is uniform in temperature, and then around the tube assembly highly insulating silicone rubber foam is used within a protective outer conduit to insulate and protect the heated line.

6.3.6 Cyclone and Secondary Splitter Oven (5PTS)

A bespoke oven was manufactured by Cardiff University's GTRC to house and heat to 60°C the AIR 6241 specified cyclone and secondary splitter (Splitter 2). A photograph of the cyclone and specially manufactured five way secondary splitter is given in Figure 14. As can be seen internal joints are, where possible, welded to reduce the chance of an internal leak developing.

The splitter is constructed from two three way splitters designed and manufactured to the specifications discussed in previous studies (SAMPLE III SC02), with no internal steps and split angles of 30°. The first splitter is an equal ⅜" three way splitter which incorporates the outlet of the 25sLPM 1µm sharp-cut cyclone (BGI), and distributes the sample to the two mass analysers namely the Artium LII-300 through the back panel of the oven and the AVL MSS through the front panel of the oven. The central line then feeds straight through into another 3 way splitter with a ¼” outlet supplying the AVL APC along with two further ⅜” lines feeding a potential size analyser and the ‘make up’ flow line.

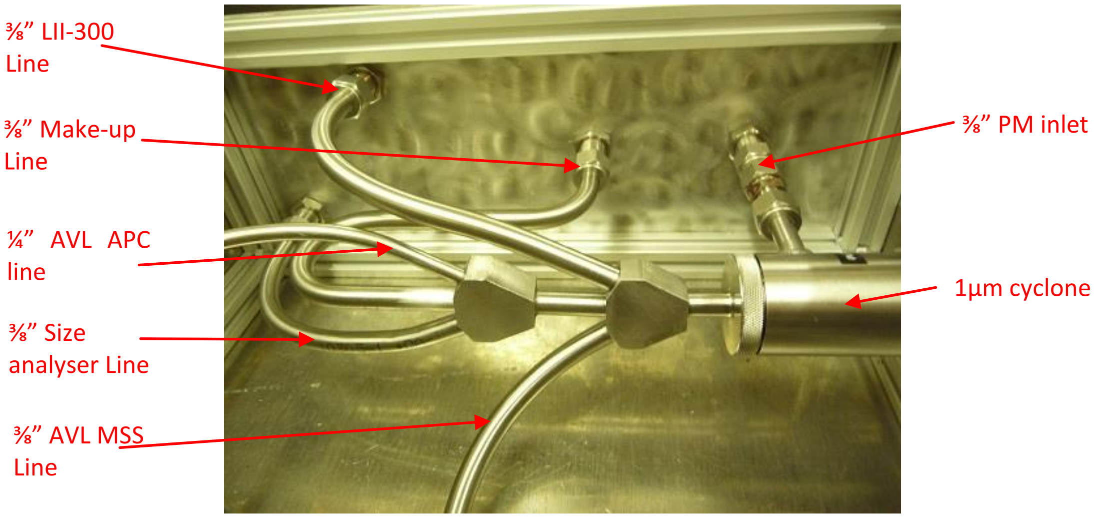


Figure 14 SAMPLE III secondary splitter and cyclone

It can be seen that the 10 bend radius specified for the sampling train is conformed to throughout the oven, as shown in Figure 15, with the exception of the flow make-up line, which does need to comply with this specification as it is concerned with the limitation of particle loss. It is also observed in this aerial view that the oven is constructed as a box within a box with insulating silicone foam ensuring the oven does not have any cold spots, whilst limiting the heat loss into the measurement racks. The oven is constructed in an ‘L’ shaped configuration in order that the AVL APC’s heated rotating diluter unit is housed within an unheated section of the oven case which enables the system to be housed within the 19” rack footprint.

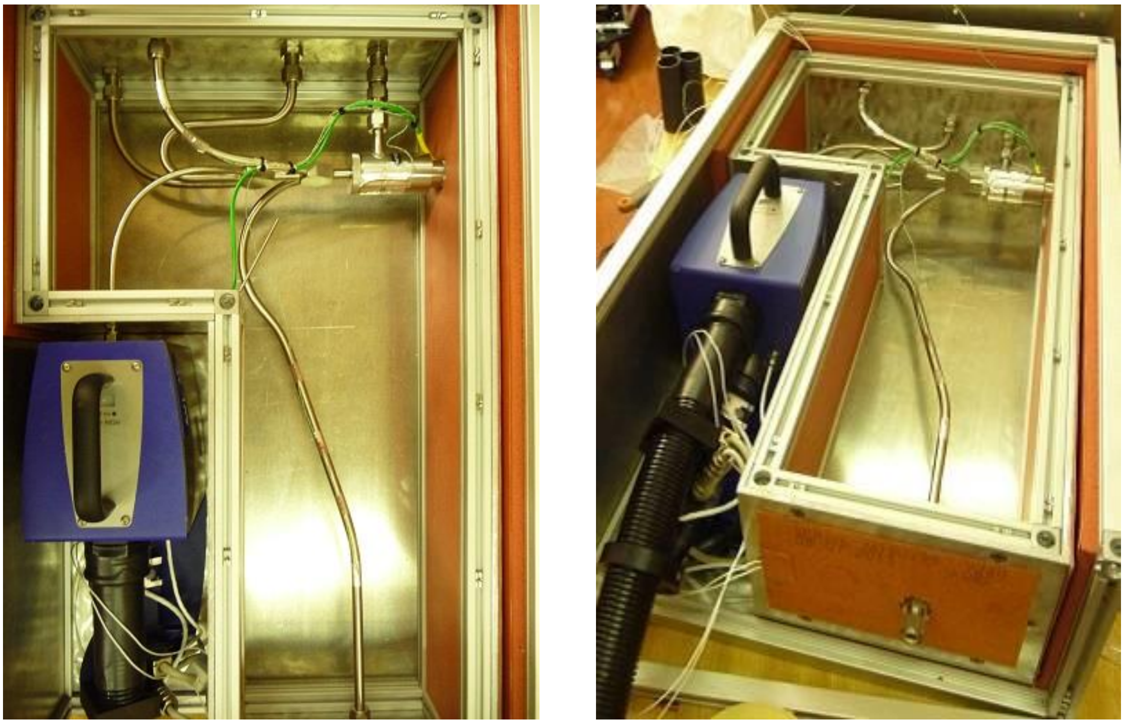


Figure 15 Cyclone and secondary splitter oven detailing position of AVL APC heated diluter

The heating elements are made-to-order self-adhesive silicone heating mats which are affixed to the top and bottom surfaces, along with extra mats which are positioned on the panels with bulkhead unions, (Figure 15 & Figure 16). This heating strategy ensures that there are no cold spots associated with the bulkheads, whilst ensuring uniform heat across the entire oven.

Figure 16 (a&b) Bulkhead and top heating mats of cyclone and secondary splitter oven (5PTS)

In making a bespoke rack mounted oven, the specific line length from cyclone inlet to analyser inlet were kept to a minimum, with line lengths (not including the flow path through the cyclone, which can't be measured) of 0.94m for the LII, 1.27m for the MSS, 0.45m for the APC and 0.45m for the DMS, which are all well within the AIR 6241 prescribed 3m.

6.3.7 Measurement Section

6.3.7.1 *Non-volatile PM number*

The EU/EASA Mobile reference system incorporates an AVL APC489-CS as its nvPM number analyser. As discussed previously (SAMPLE III.SC02) this unit is based largely on the PMP (Particle Measurement Programme – for automotive regulation) AVL APC with the exception of an added catalytic stripper after the evaporation tube. Due to this being the only commercially available AIR specified number counter and VPR, EASA purchased a unit for the SAMPLE III.SC02 contract. However, the specifications of the CPC in AIR 6241 meant the original TSI 3772 CPC installed was non-compliant, hence the SAMPLE III consortium under contract SAMPLE IIISC04 upgraded the CPC to a compliant TSI 3790-E model. As such, this modified unit has been built into the SAMPLE III.SC03 designed EU/EASA mobile reference system. A full description of functioning principle has been given previously (SAMPLE III.01) thus will not be discussed further at this time.

Figure 17 Photograph of commercially available VPR incorporating a catalytic stripper

When the penetration performance specifications from the SAE E31 PM measurement section of the draft working document were conducted for the three reference systems it was found that with the additional Catalytic Stripper, the penetration performance measured was at some particle sizes very close to or slightly lower than the values quoted in the DWD (which were based on SAMPLE III and AVL original recommendations) as such, before the AIR 6241 was balloted these numbers were slightly relaxed. The new figures for penetration adopted, with the previous figures of the DWD are given in (Table 2); with further discussion given later in section Manufacturers Calibration 6.4.1.1.

Table 2 AIR6241 performance specifications for VPR & number counter

Particle Size (nm)	15 nm	30 nm	50 nm	100 nm
VPR Transmission Efficiency Required (previous DWD)	≥ 30 % (> 50%)	≥ 55% (> 70%)	≥ 65% (> 70%)	≥ 70% (> 70%)
Volatile Removal Efficiency (previous DWD)	99.9% (99.5%)	99.9% (99.5%)	- (99.5%)	- (99.5%)
Target loadings (previous DWD)	10000 (10000)	50000 (100000)	-	-

6.3.7.2 *Non-volatile PM Mass*

As discussed earlier the SAE E31 PM subcommittee defined that there should be two mass analysers within any reference systems. As such it was decided that one of each of the currently proposed technologies namely AVL MSS and Artium LII, both calibrated in the manner prescribed by AIR6241 should be included in each reference system, photographs of the two analyser types are given in Figure 18. It was also decided that each system should allocate one analyser as the primary analyser which must be serial number locked to the specific reference system whilst the secondary analyser could be exchanged for any suitably calibrated unit of the same technology. The EU/EASA reference system has a Cardiff University sponsored Artium LII-300 analyser as its primary analyser and an AVL MSS as its secondary measurement device which was kindly loaned to the SAMPLE III consortium by AVL.

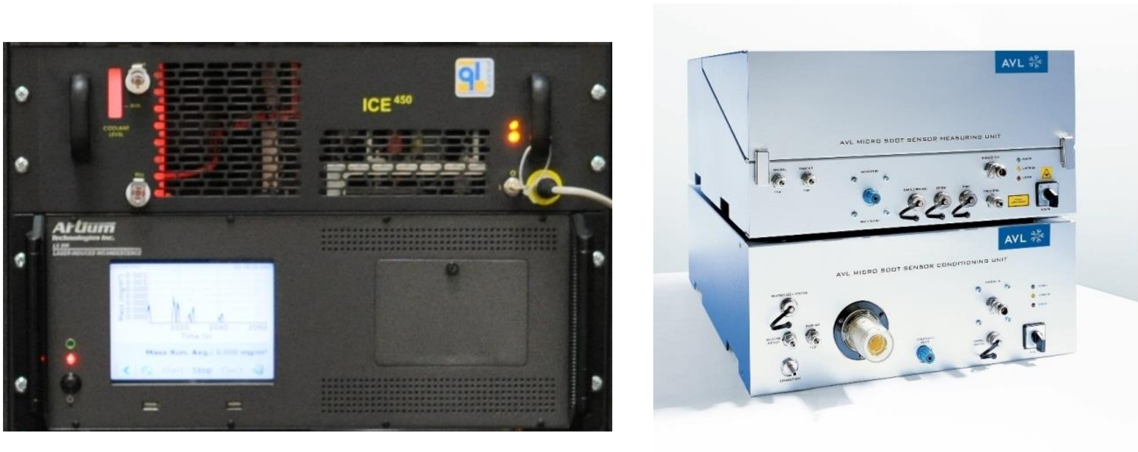


Figure 18 Artium LII-300 and AVL MSS nvPM mass instruments

6.3.8 Gas Transfer System (GTS)

The gas transfer system connects and conditions the raw CO_2 from the primary splitter in 3PTS to the gas analyser in the measurement section. In order to comply with all specifications outlined in Annex 16 (ARP1256) for gaseous CO_2, the GTS in the EU/EASA Mobile reference system consists of a 24.3m carbon loaded PTFE line identical in construction to that used and described for 4PTS. If the inlet to the dilution box is placed at the Probe exit then the GTS line is also compliant to measure SN as per ARP1179. The sample is pumped down the line by a heated head diaphragm pump (KNF PM27754-036.11).

The heated head is controlled to 160ºC by one of the systems temperature controllers described later in section 6.3.9.2. As only CO_2 is currently being measured by the GTS the sample is then cooled in a stainless steel coil before entering a coalescing filter which removes water droplets and some PM, before passing through a further stainless steel mesh particle filter (1 micron).

At this point the sample is then split with 1.5sLPM being pumped through a gas chiller (at 5ºC) via a stainless steel flow control regulator to the NDIR measurement cell. The remaining sample passes to one of the mass flow controllers described in section 6.3.9.1 which is set to comply with AIR 6241 flow conditions and where 3PTS inlet pressure permits Annex 16 residence time constraints.

6.3.9 System Control and Data Acquisition

6.3.9.1 *Mass Flow Control*

In order to achieve all of the flow conditions stipulated for the PM and gaseous sampling, in AIR 6241 a bespoke Mass Flow Unit was designed and manufactured by Cardiff University's GTRC. The unit incorporates 3 nominally identical mass flow controllers (Bronkhorst EL-Flow F-201CV-10K-ABD-22-V) which offer mass flow control in the flow range of 0-15sLPM at an accuracy of ±0.5% RD (residual deviation) plus ±0.1% FS (full scale). Photographs of the bespoke MFC unit are given below in Figure 19.

These units are controlled using a user friendly digital control and readout screen (Bronkhorst BRITE) which is positioned in the front panel of the unit and allows the MFC's to be individually controlled and visualised by the operator independent of the systems control PC.

Figure 19 Photographs of Internal setup, back panel and front panel of 3 channel MFC control unit

The MFC's also have an analogue output which means that the units can be remotely logged by connecting to the output sockets on the back of the MFC unit.

6.3.9.2 *Temperature Control*

When the EU/EASA mobile reference system was designed it was calculated that there were 12 individual heated sections that required controlling namely; the 2x 2m heated lines in 2PTSa, GTS section in 3PTS, primary splitter in 3PTS, diluent heater in 3PTS, primary diluter in 3PTS, 4PTS sample line, GTS sample line, GTS sample pump, cyclone and secondary splitter oven 5PTS and the two mass analyser sample lines. Four 3 channel temperature controllers were manufactured. A photograph of the front and back panels of the controllers is given in Figure 20.

Figure 20 Photographs of back panel and front panel of 3 channel heater control unit

Each temperature channel has two PID (proportional integral derivative) control modules (Eurotherm 3065) one controlling off a set point thermocouple and the other acting as an alarm monitor which cuts power to the entire control circuit should the temperature reach a pre-set threshold, this allows the operators to ensure that no additional damage is done should there be a failure in the heating control loop.

6.3.9.3 *3PTS Control and Data Acquisition*

The 3PTS control system design was based upon the successful hardware architecture of the SAMPLEIII SC02 3PTS control system. However, the design was upgraded to minimise the packaging size and fit into a 19” rack-mount case.

The control system box (Figure 21) can be run in 2 modes: manual or computer. In manual mode the 3PTS valves (Diluent, Isolation and Spill) can be operated using switches. In computer mode the valves can be operated electronically and in addition the differential pressure across the diluter, which acts as a set-point for the spill control valve, can be changed. An emergency stop button is also included in case immediate shutdown is required (isolates 4PTS and opens spill valves).

The data acquisition within the control system box consists of 4xCompact-rio slot hardware, which provides control of the valves within the dilution box on the gantry and also data acquisition of temperature and pressure measurement sensors.

The control and data acquisition software (Labview based) was also upgraded to include the additional spill ball-valve operation. The control system box also contains extra non-3PTS data acquisition inputs:

10x thermocouples and 6x4-20mA sockets

7x thermocouple slots are utilised to record the temperatures of 4PTS, 5PTS (oven wall, cyclone, LII umbilical, MSS umbilical), GTS and ambient. 3 x thermocouple slots are spare.

In the future the 6x 4-20mA sockets could be used to record the 3-channel gas analyser and 3x mass flow controller (MFC) outputs. However, for the initial build, due to time constraints in system construction a simple USB data acquisition module (OMEGA 2401) was utilised to record the CO_2 and MFC data at the Zurich test campaign.

Figure 21 Photograph of 3PTS Control and Data Acquisition system

6.3.10 System Racking and Power

In order to ensure the system was sufficiently mobile it was decided that the entire system be built into shipping 'flight cases' capable of being transported in a standard size rental van. As the majority of the analysers were 19" rack compatible it was decided to base the concept around a number of suitably sized 19" rack shock mounted flight cases which would be suitable for both transport and operation with minimal wiring and plumbing requirements to be performed at the test facility.

After consolidating the final design it was shown that the control, data acquisition, gas distribution and measurements sections of the sampling system could be fitted into three identical custom made shock mounted rack cases. Technical drawings of the cases are given below in Figure 22.

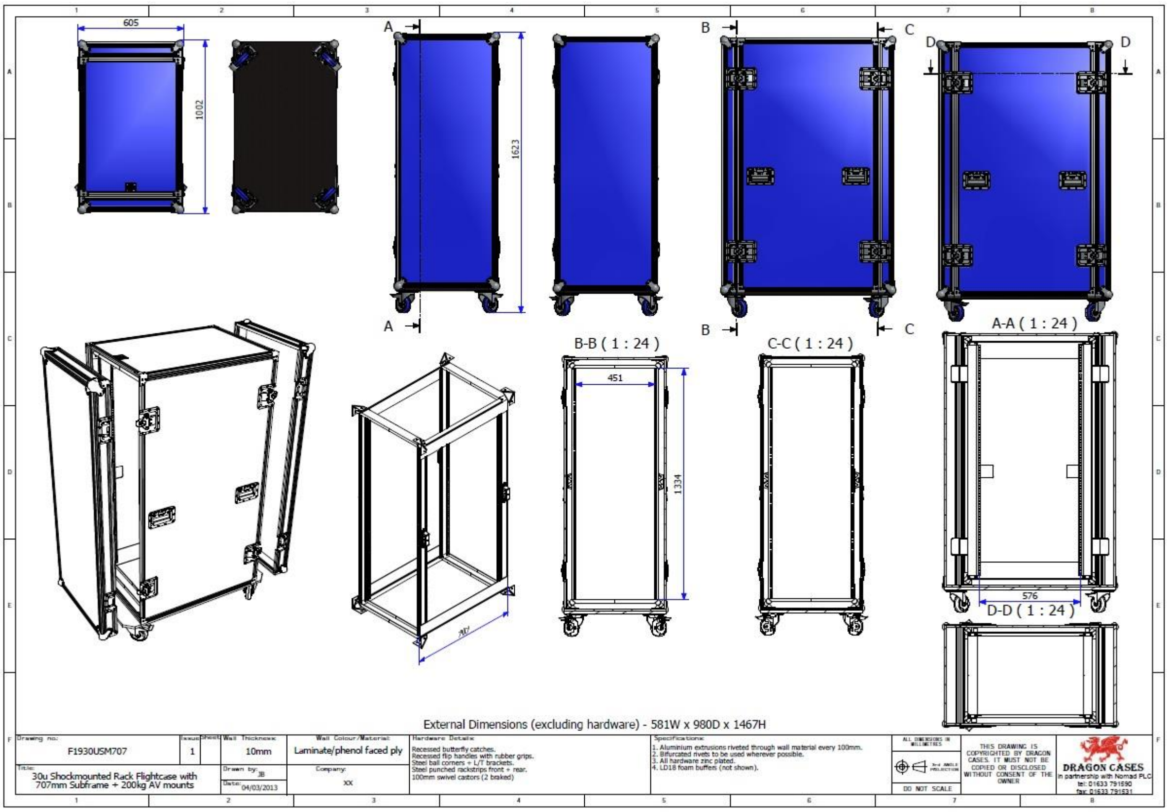


Figure 22 Technical drawing of 19" Shock mounted flight cases used for the EU/EASA mobile reference system

The fully assembled rack mounted EU/EASA reference system with the instrumentation, data acquisition and control is shown below in Figure 23

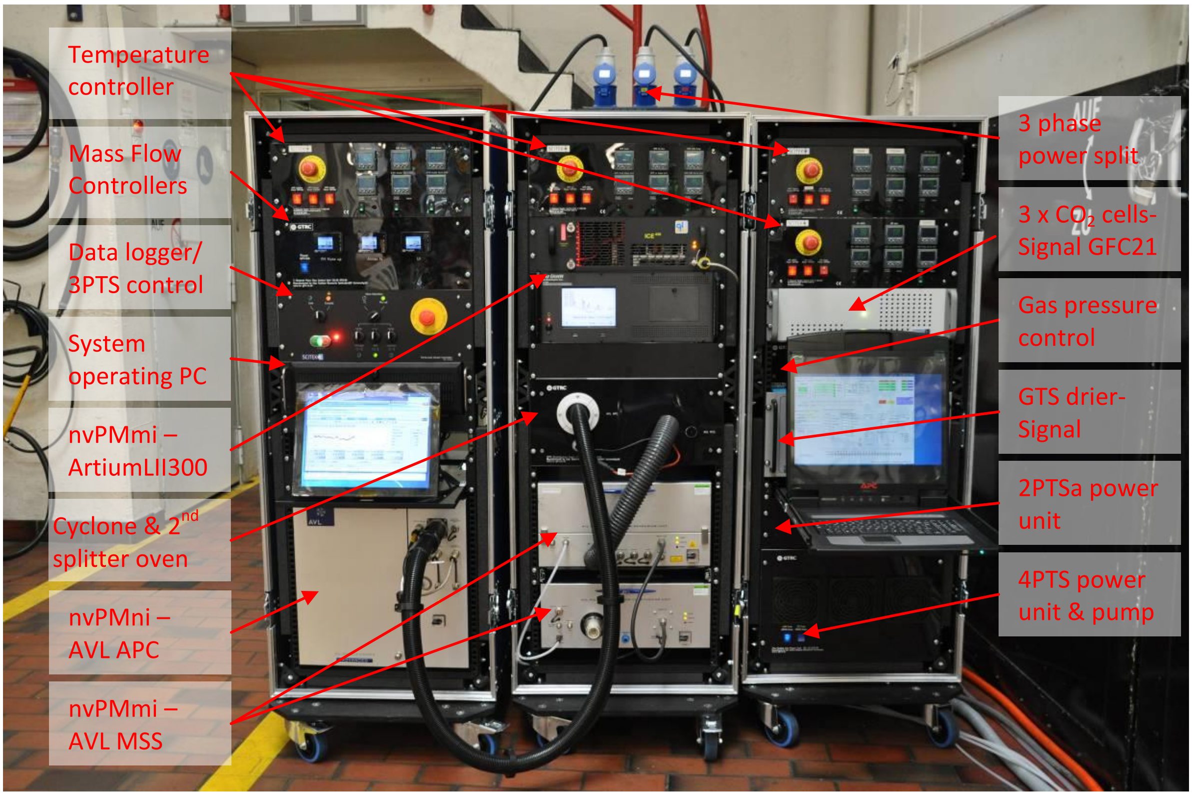


Figure 23 Control, data acquisition and measurement sections of EU/EASA mobile reference system

6.3.11 Parts list of EU/EASA Mobile Reference System

A detailed parts list of all of the components described in section 6.3, is presented in Table 3.

Table 3 Parts List of EU/EASA Mobile Reference System

System Part	Description	Manufacturer
2PTSa	10mm Three way splitter	GTRC (bespoke)
	2 off 2m grounded PTFE Heated Lines and power transformers	Signal Inst
	Power transformer unit (Estrasil transformers)	GTRC (bespoke)
3PTS Dilution Box & control	⅜" Three way splitter	GTRC (bespoke)
	DI-1000 eductor diluter	Dekati
	DH-1723 Nitrogen Heater	Dekati
	PM line- ⅜" Stainless steel tube & fittings	Swagelok
	Diluter Vent Line- ½" Stainless steel tube	Swagelok
	PM line- ⅜" Stainless steel tube & fittings	Swagelok
	Nitrogen supply line- ⅜" Stainless steel tube & fittings	Swagelok
	Exhaust spill line- ½"steel tube and fittings	Swagelok
	160°C spiral wound silicon trace heating	Watlow
	60°C spiral wound silicon trace heating	Watlow
	Control & data logging system, computer, touch screen, national instruments compact rio,	SCITEK (Bespoke)
	Pneumatic solenoids and regulator set for valve control	Norgren
	Steel enclosure box, 83cm x 35cm x 35cm	SCITEK (Bespoke)
	PM Sample line isolation valve- T63m ⅜" high temperature ball valve and Pneumatic controller	Swagelok
	Exhaust spill control valve- ½" 8021 high temperature control valve and 8049 series positioner	Schubert & Saltzer
	Exhaust spill isolation valve- ½ " high temperature ball valve	Swagelok
	Nitrogen isolation valve- ⅜" ball valve and Pneumatic controller	Parker
	PM inlet thermocouple, logging 'k' type in bespoke flush mount housing	TC Direct
	Nitrogen high temperature Alarm, 'k' type	TC Direct
	Eductor Diluter vent line temperature, logging, 'k' type	TC Direct
	PM sample temperature, 'k' type in bespoke flush mount housing	TC Direct/ SCITEK
	PM Sample line control temperature, 'k' type 60°C control thermocouple	TC Direct
	PM Sample line control temperature, 'k' type 160°C control thermocouple	TC Direct
	Pressure differential pressure transducer (200mbar)	Druck
	Absolute pressure transducer for nitrogen inlet pressure monitoring (2500mbarG)	Druck
4PTS	25m grounded PTFE Heated Lines	Signal Instruments
	Power transformer unit (Estrasil transformers)	GTRC (bespoke)
5PTS	Thermally controlled Oven	GTRC (bespoke)
	Self adhesive silicone heaters	Thorne & Derrick
	K' Type Thermocouples	TC Direct
	1 µm Sharp cut Cyclone	BGI
	⅜" Three way splitter	GTRC (bespoke)
	Three way ⅜"-2x⅜"- 1x ¼" splitter	GTRC (bespoke)
	⅜" and ¼" stainless steel lines & bulkhead fittings	Swagelok
Measurement Section	LII-300 power supply and measurement unit	Artium
	AVL APC including TSI 3790e CPC	AVL
	AVL MSS conditioning and measurement unit	AVL (loan)
	Make-up & LII gas flow pump	KNF
	0.75m SS heated lines (watlow trace heating)	GTRC (bespoke)
GTS	25m grounded PTFE Heated Lines and power transformers	Signal Instruments
	Heated Head GTS Pump	KNF
	¼" SS & PFA tubing	Swagelok
	Coalescing Filter	Norgren
	SS Particle filter	Headline Filters
	Gas chiller and dual pump unit	Signal Instruments
	7 channel regulator unit (Norgren & swagelok)	GTRC (bespoke)
	3 Channel NDIR CO_2 analyser	Signal Instruments
Control & Data Acquisition	Control and data logger (National Instruments compact RIO hardware)	SCITEK (Bespoke)
	4 off 3 channel alarmed heater controllers	SCITEK
	3 channel Mass Flow Control Unit (Bronkhorst EL-Flow & BRITE)	GTRC (bespoke)
	19" Rack mountable key board & Monitor	APC
	15" touch screen monitor	iiyama
	computer	Amplicon
Racking & Power	4 x 19" shock mount racks	Dragon cases
	1 x Travelling case	RS
	2 x 19" sliding shelf & 20 x 19" shelf pair	Dragon cases
	6 x Sliding rack drawers	Adam Hall Hardware
	3 off 32A power distribution and monitoring units	GEIST
	32A 3-Phase splitter	Essential Supplies
	32A 3-Phase extension cable	RS
	Cabling Power and thermocouple	RS

6.4 EU/EASA Mobile Reference System Calibrations

To ensure that the reference 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. Below are explanations of the calibrations performed.

6.4.1 Non Volatile Number Measurement System Calibration

6.4.1.1 *Manufacturers Calibration*

As specified by AIR6241 the AVL APC with associated TSI CPC was sent back to AVL Graz for an annual AIR approved calibration. Within this calibration, VPR performance in terms of penetration and volatile particle removal is checked along with the number counters linearity and counting efficiency slopes.

Unfortunately, when the AVL APC was returned after calibration it was noticed that there were some discrepancies in the calibration certification (Appendix 10.1.1), namely that the ambient temperatures quoted for the CPC calibration were obviously in error (96.6°C). Also it was observed that numerous requirements of AIR6241 such as penetration performance for 15nm particles were not quoted in the documentation, which made proving conformity with AIR 6241 difficult.

On further inspection of the certificate it was also noted that AVL had reset the catalytic stripper temperature back to 300°C from the 350°C quoted in AIR6241. Unfortunately due to the short time period between receiving the unit and the test campaign it was not possible to return the device for an AIR 6241 recalibration. On consultation with AVL representatives it was decided the only course of action was to conduct a pre-test inter-comparison (described in section 6.4.1.3) with the North American and Swiss systems to check the offsets caused by discrepancies in the calibration procedure were within the expected measurement uncertainty, then send the unit back for recalibration after the study was completed so new factors could be applied to the dataset, if deemed necessary.

On comparing the EU/EASA documentation with the North American and Swiss certificates it was observed that they also had a lack of detail in their documentation and in the case of the Swiss system their catalytic stripper had also been reduced to 300°C. These errors in calibration meant that the only VPR unit that appeared to be within AIR 6241 specification was that of the North American system.

Other factors such as CPC linearity and counting efficiency were within specification for the EU/EASA system with a maximum variation of -4.74% observed for the linearity compared to the allowable 10%, and counting efficiencies of 53.2% and 98.1% being quoted for 10 & 15nm particles respectively compared to the allowable 50% and 90%. On comparison with the North American and Swiss system CPC’s it was observed that all three were within specification, however the Swiss and North American systems were more comparable to each other with each seeing larger linearity offsets of approximately -7% with counting efficiencies of circa 76% and 92% for 10 &15nm particles, thus the two other reference systems have different counting efficiency gradients compared with that of the EU/EASA CPC.

Discussion between the SAMPLE III consortium and AVL representatives have led to potentially a new certificate being issued for AIR6241 compliant calibrations. The new certificate format will detail all of the requirements of AIR 6241 (an example of how such a certificate may look is given in Appendix 10.2, though it should be noted that the volatile removal temperature is currently missing from this example). It is suggested that the SAE E31 number team should coordinate with AVL to develop a suitable certificate that easily shows compliance with AIR 6241 and future ARP's.

As penetration performance could not be suitably determined from the certification, AVL were asked to send details of the actual performance of penetration for each of the reference units which were presented numerically and graphically to the SAE E31 at their Annual meeting Ispra 2013, the details of which are given below in Table 4 & Figure 24.

Table 4 Numerical penetration performances of three reference system VPR at different particle sizes

	Particle Mobility Size (nm)			
S/N (ref. system)	100	50	30	15
410C (North American)	75%	71%	61%	33%
409C (Swiss)	77%	71%	59%	34%
382a (EU/EASA)	77%	72%	62%	32%
Revised spec.	≥70%	≥65%	≥55%	≥30%

As discussed earlier in Table 2 the result of this comparison meant that the penetration values originally in the SAE E31 Non Volatile PM DWD had to be revised in AIR 6241 so as the only currently commercially available unit could meet the specifications.

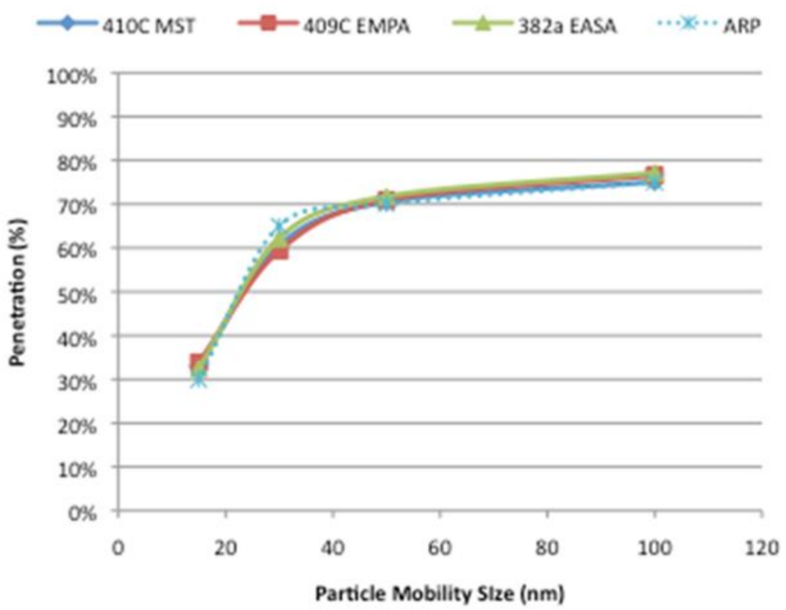


Figure 24 penetration performances of three reference system VPR at different particle sizes

6.4.1.2 *Pre test Dilution Factor Check*

As detailed in AIR 6241 in order to calculate the dilution factor for the AVL APC at the different dilution set-points used during the testing it is a requirement that the value be measured using gaseous measurement prior to testing. As such using pure CO_2 the EU/EASA mobile reference system was checked at PCRF values of 100 and 250 with the values measured plotted in Figure 25. Note that the PCRF acronym relates to an automotive industry number parameter which is a multiplication correction factor combining dilution factor and VPR particle loss (effectively for a 50nm diameter particle). Therefore a PCRF set-point equals a dilution factor set-point in the AVL unit. During 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 a specific PCRF set-point and does not include correction for particle loss within the instrument.

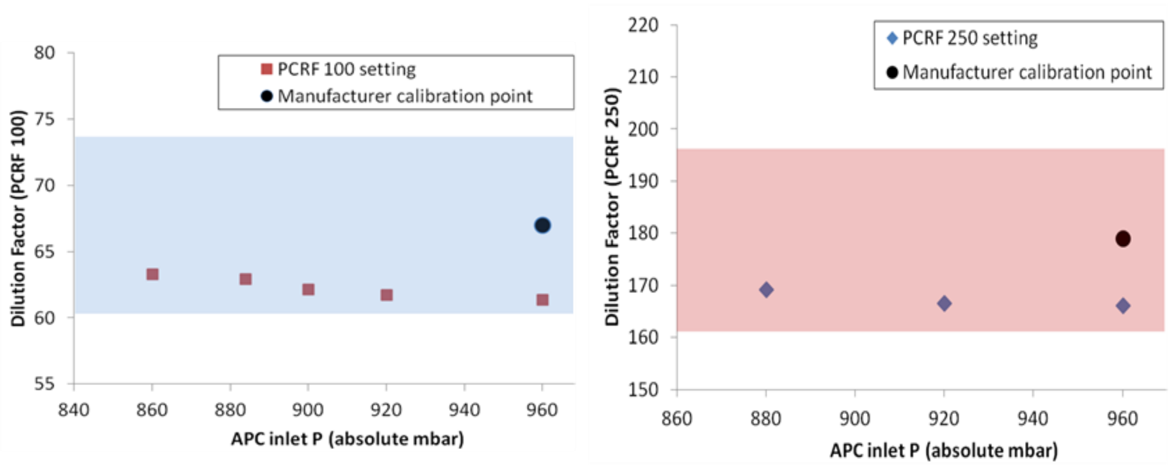


Figure 25 Pre-test VPR Dilution Factor Performance Check with pressure sensitivity

As can be seen when the dilution factor was measured for a PCRF of 100 it was approximately 61 compared with the value of 67 quoted by AVL when the unit was originally calibrated. The dark band shows the tolerable drift specified in AIR6241 which allows for a 10% difference in dilution factor compared with the manufacturers quoted value; it is clearly observed that all values do lie within this tolerance. For PCRF 250 again the EU/EASA mobile reference system was within tolerance measuring a dilution factor of 166 compared to the calibrated value of 179.

The SAMPLE III consortium observed that the calibration was performed at ambient pressure which is not the pressure at which the device is typically operated, thus it was decided that additional dilution factor checks (in addition to those prescribed in AIR 6241) should be conducted at reduced pressures to ensure the dilution factor applied to the data was representative of that actually observed during testing. As can be seen the dilution factor at reduced pressures is higher than those at ambient so it is advised that this additional detail should be added to the ARP in order to reduce uncertainty.

On consultation with the Swiss and North American reference operators it was found that their APC dilution factors were also different to those quoted during the manufacturer calibration, details of which are given in Table 5.

Table 5 Calibrated and measured dilution factors for three reference AVL APC's at ambient sample pressure inlet conditions and at low/typical sample pressure conditions (in brackets)

Reference System	PCRF	Calibration DF	Measured DF (at low/typical sample pressure)
Swiss	100	66.5	66.1
	250	170	159.9
North American	100	65	67.8
	250	170	165.2
EU/EASA	100	67	61.3 (63)
	250	179	166.1 (167)

As can be seen all reference systems are within specification but this study highlights the importance of pre-test dilution factor checks if real time online measurement of dilution factor is not being undertaken.

6.4.1.3 *Pre-test Laboratory Inter-comparison of AVL APC units*

As discussed earlier in the AVL manufacturers calibration section due to a misunderstanding at AVL both the EU/EASA mobile reference system and Swiss fixed reference system AVL APC units had their catalytic stripper temperatures reduced from the 350°C prescribed by AIR 6241 to 300°C, which is the temperature of the evaporation tube prescribed by the PMP protocol. As such only the North American mobile reference system was truly calibrated to the AIR recommendations.

To ascertain whether this temperature difference would greatly affect the PM readings witnessed at different PCRF's during the test campaign, the three APC units were compared against each other using a Jing mini-CAST soot source. A schematic representation of the laboratory set-up is given in Figure 26. As the North American AVL APC unit was correctly calibrated this was used as the reference and the other two units were compared sequentially.

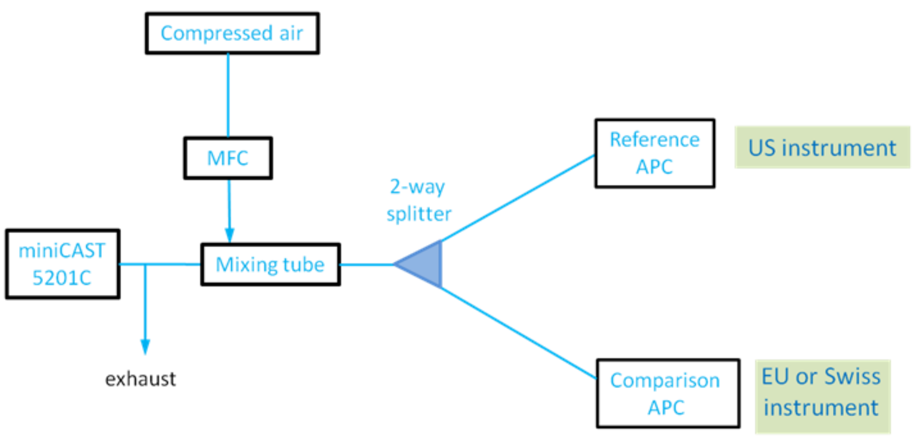


Figure 26 Schematic representation of experimental set-up of pre test Laboratory Inter-comparison of AVL APC units

The mini-cast set points used for this study are presented below in Table 6. These values were typically used for the comparison; however, additional Nitrogen was used to change the soot GMD (Geometric Mean Diameter), to facilitate a size dependency sensitivity study.

Table 6 mini-CAST gaseous set points used for pre-test Laboratory Inter-comparison of AVL APC units

miniCAST 5201C Set points	
Propane	60 ml/m
N_2	0 ml/m
Oxidation air	1.55 l/m
N_2	7 l/m
Dilution air	20 l/m

It was observed that poor repeatability was observed between the reference system and the other units immediately after the catalytic strippers were increased from 300 to 350°C, however after allowing temperature stabilisation a comparison was made.

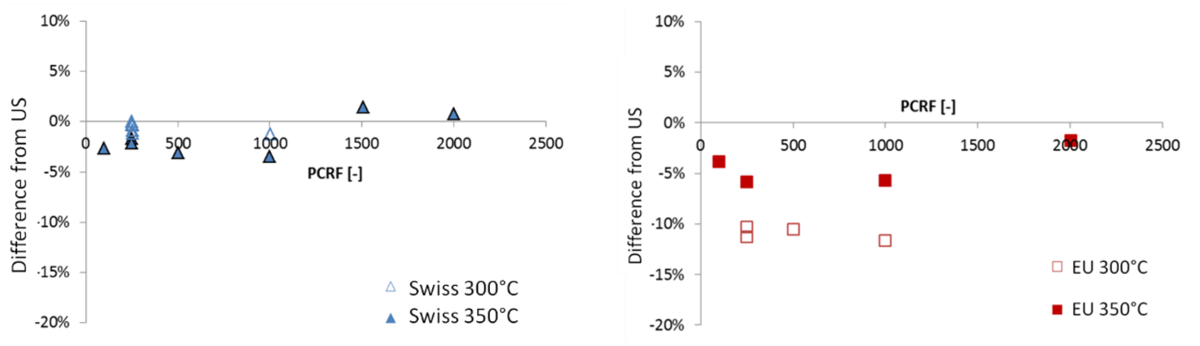


Figure 27 Inter-comparison of Swiss and EU/EASA APC to North American reference

As can be seen the Swiss and North American systems which were calibrated simultaneously by the manufacturer displayed very good agreement with the increase in Catalytic Stripper temperature making little difference to the comparison. It is also observed that the EU/EASA system was within 12% of the North American reference with the catalytic stripper at 300°C, however the agreement was closer to 5% when the temperature was increased to 350°C, which is within the expected uncertainty given that 10% linearity is permitted within the CPC alone. As such it was decided that it was possible to carry on with the engine testing with only a 5% uncertainty occurring between the AVL APC's.

As it was noticed that there were significantly different counting efficiencies noted at 10nm between the EU/EASA and the North American and Swiss CPC's, as discussed earlier in the manufacturer calibration section (6.4.1.1), it was decided to investigate if the EU/EASA APC had a constant offset, to the North American reference APC across a range of particle sizes. As such additional Nitrogen was used to un-quantifiably (due to lack of size instrumentation for his specific experiment) adjust the soot size distribution and assess the relative number count offset. A graphical representation of the findings is given in Figure 28.

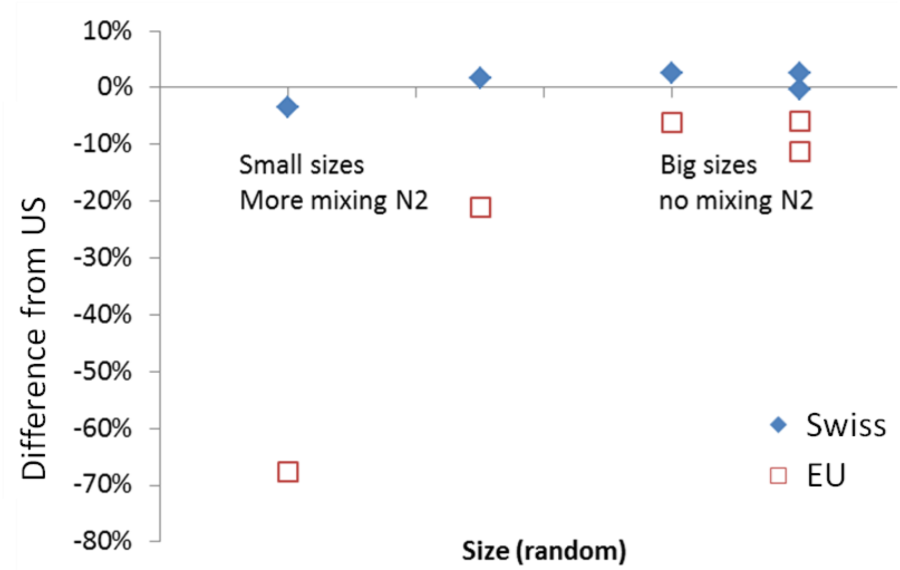


Figure 28 Size sensitivity of three reference APC's to mini-CAST soot

It is observed that the North American and Swiss APC's again show very good agreement within 2.5% across all size ranges tested. However as possibly expected, due to the different CPC counting efficiency, the EU/EASA APC shows a remarked increase in counting offset as the perceived soot size decreases resulting in a 70% discrepancy for the smallest particles counted.

From this size sensitivity study it was expected that if a significant number of small (<15nm) particles were transported through the sampling system during the engine measurements, then the EU/EASA APC would read lower than the North American and Swiss systems.

6.4.2 Non Volatile Mass Analyser Calibration

In order to comply with AIR 6241 it was necessary for the mass analysers to be traceably calibrated to NIOSH 5040. NRC Canada (the national standards laboratory of Canada) with financial support from Transport Canada conducted the first AIR 6241 type certification and annual calibrations of all six of the reference mass analysers being used for the Zurich test campaign[a]. A schematic representation of the set-up used is given in Figure 29.

[a] Kevin Thomson, Fengshan Liu and Greg Smallwood, "System for the absolute calibration of black carbon mass concentration measurement instruments",, American Association of Aerosol Research, 32nd Annual Conference, Portland, OR, USA, September 2013

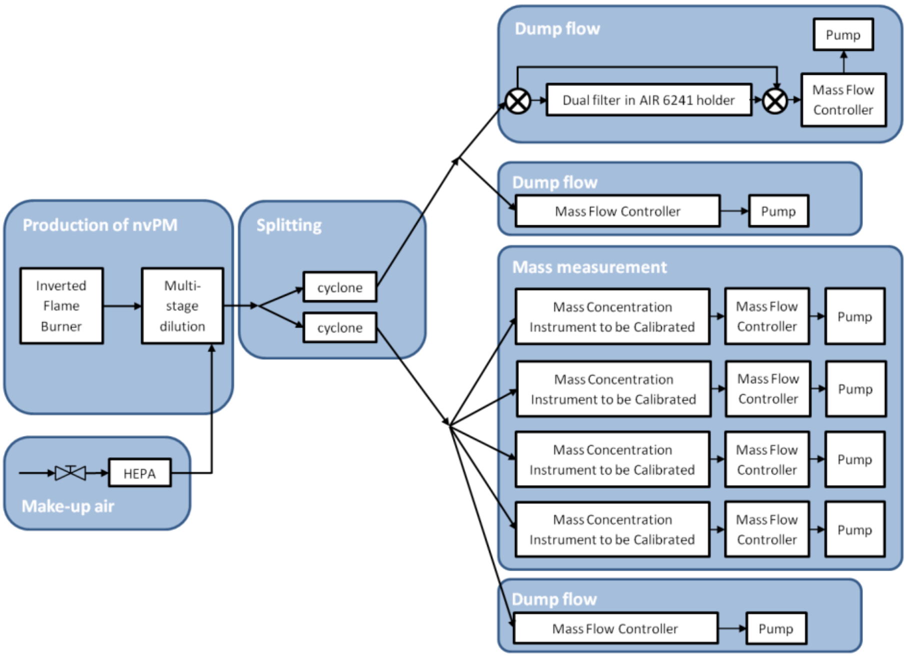


Figure 29 Schematic representation of experimental set-up used by NRC Canada for AIR 6241 approved annual calibration of mass analysers

Details of the actual data for the EU/EASA mobile reference systems mass analysers are given in the following sections.

6.4.2.1 *Artium LII 300*

The Artium LII-300 was calibrated according to the standard annual AIR 6241 compliant calibration being compared with NIOSH 5040 at 3 target loadings of 0.1, 0.25 & 0.5 mg/m^3. The data comparing the original LII value to NIOSH 5040 and the adjusted values after a calibration factor is applied to the LII-300 are given below in Figure 30 & Table 7.

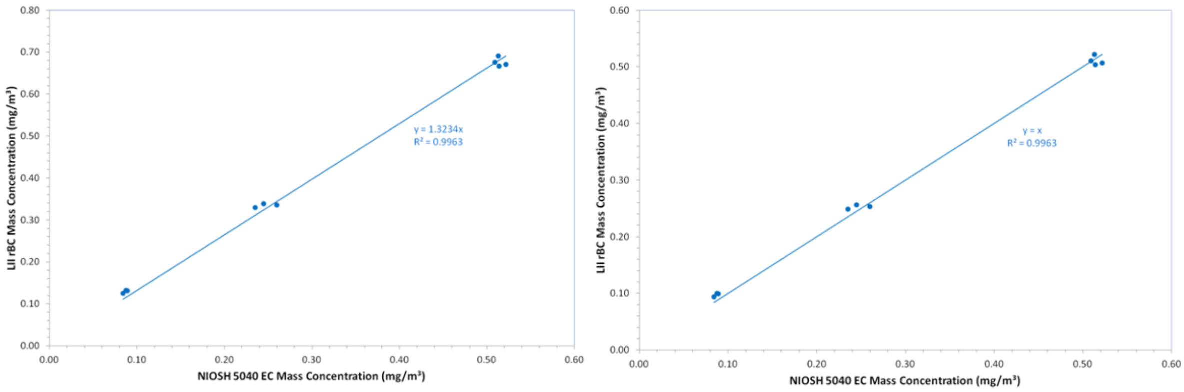


Figure 30 (a&b) EU/EASA Mobile Reference System Artium LII-300 (SN0435), Pre and post Linearisation calibration data respectively, conducted by NRC Canada to AIR 6241 (NIOSH 5040) specifications

As can be seen before the calibration factor was applied to the new analyser there is a discrepancy of 32% seen between the analyser output and NIOSH 5040. However, after a calibration factor of 0.7556 is applied then unity is agreed with NIOSH 5040.

Table 7 Summary of EU/EASA Mobile Reference System Artium LII-300 (SN0435), Pre and post Linearisation calibration data, conducted by NRC Canada to AIR 6241 (NIOSH 5040) specifications

Target Mass (mg/m^3)	NIOSH 5040 EC (mg/m^3)	Pre Cal. LII BC (mg/m^3)	Post Cal. LII BC (mg/m^3)
0.100	0.0873	0.1324	0.1001
0.100	0.0889	0.1315	0.0993
0.100	0.0842	0.1248	0.0943
0.250	0.2448	0.3388	0.2560
0.250	0.2597	0.3356	0.2536
0.250	0.2352	0.3295	0.2490
0.500	0.5129	0.6910	0.5221
0.500	0.5092	0.6762	0.5109
0.500	0.5138	0.6669	0.5039
0.500	0.5218	0.6708	0.5069
Slope:		1.3234	1.0000
Standard Error:		0.0132	0.0100
Correlation:		0.9991	0.9991
Cal. Factor:		**0.7556**	

6.4.2.2 *AVL MSS*

The MSS was calibrated according to a full type certification test (as the MSS type instrument had not yet undergone such a test previously) hence 4 target loadings of 1.0, 0.5, 0.1 & 0.05 mg/m^3 were conducted with 6 repeats attempted at each point. The data comparing the original MSS value to NIOSH 5040 and the adjusted values after a calibration factor is applied to the MSS are given below in Figure 31 & Table 8 respectively.

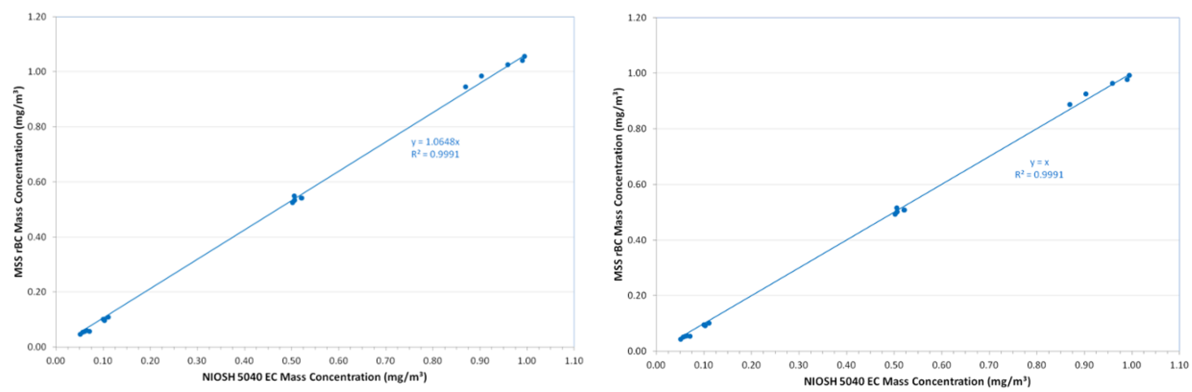


Figure 31 (a&b) EU/EASA Mobile Reference System AVL MS (SN0435), Pre and post Linearisation calibration data respectively, conducted by NRC Canada to AIR 6241 (NIOSH 5040) specifications

It is witnessed that before the calibration factor was applied to the analyser which had previously been calibrated using an OC/EC technique, there is a discrepancy of 6% seen between the analyser output and NIOSH 5040, however, after a calibration factor of 0.9391 was applied then unity is demonstrated with NIOSH 5040.

Table 8 Summary of EU/EASA Mobile Reference System AVL MSS (SN0273), Pre and post Linearisation calibration data, conducted by NRC Canada to AIR 6241 (NIOSH 5040) specifications

Target Mass (mg/m^3)	NIOSH 5040 EC (mg/m^3)	Pre Cal. MSS BC (mg/m^3)	Post Cal. MSS BC (mg/m^3)
1.0000	0.9947	1.0559	0.9916
1.0000	0.9903	1.0406	0.9772
1.0000	0.9591	1.0261	0.9636
1.0000	0.9035	0.9848	0.9248
1.0000	0.8692	0.9457	0.8881
0.5000	0.5058	0.5495	0.5160
0.5000	0.5211	0.5416	0.5086
0.5000	0.5202	0.5413	0.5083
0.5000	0.5054	0.5329	0.5005
0.5000	0.5063	0.5346	0.5020
0.5000	0.5016	0.5246	0.4927
0.1000	0.1001	0.1019	0.0957
0.1000	0.1026	0.0998	0.0937
0.1000	0.1024	0.0974	0.0915
0.1000	0.1030	0.0990	0.0930
0.1000	0.1108	0.1082	0.1016
0.0500	0.0507	0.0470	0.0441
0.0500	0.0611	0.0579	0.0544
0.0500	0.0711	0.0573	0.0538
0.0500	0.0645	0.0596	0.0560
0.0500	0.0567	0.0538	0.0505
Slope:		1.0648	1.0000
Standard Error:		0.0048	1.0000
Correlation:		0.9996	1.0000
Cal. Factor:		**0.9391**	

6.4.2.3 *Pre-test Laboratory Inter-comparison of Mass analysers*

To ensure that all the mass analysers had not been effected by the transport from their joint calibration at NRC Canada, NRC performed a pre and post 3 way inter-comparison test, laboratory (on-site at SR Technics) based inter comparison of all 6 of the reference mass analysers at SR Technics Zurich using a Jing mini-cast propane burner soot source. A schematic representation of the experimental set-up is given below in Figure 32.

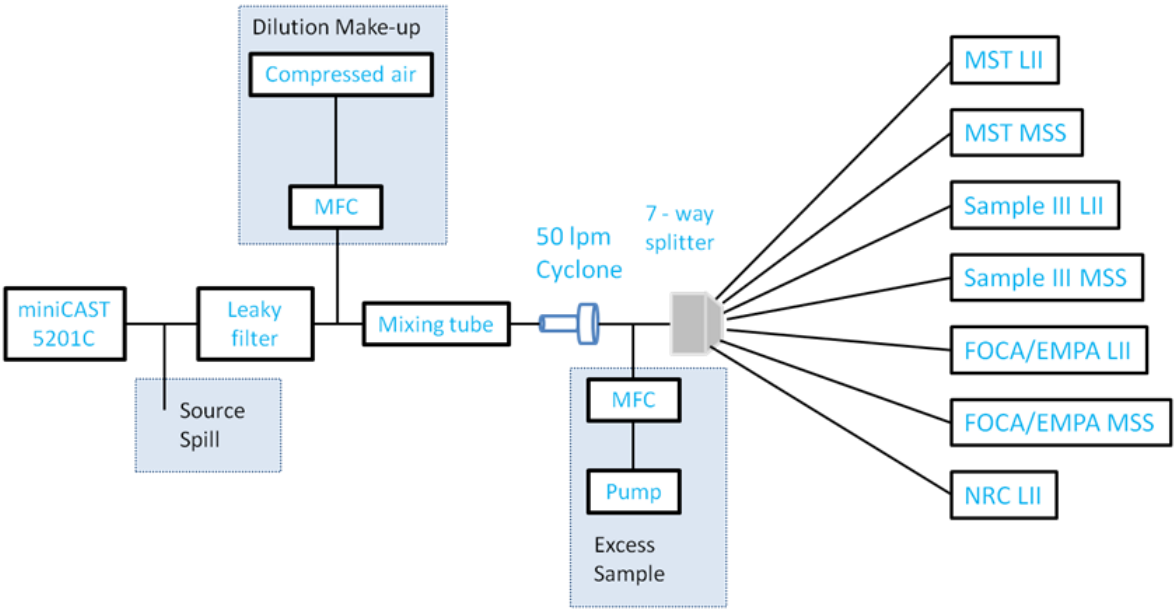


Figure 32 Schematic representation of experimental set-up of pre-test Laboratory Inter-comparison of mass units

The flow rates to each of the analysers is given in Table 9, with the make-up pump being used to ensure that the cyclone is operating at its correct flow rate.

Table 9 Flow rates of sample lines used for pre-test laboratory inter-comparison of mass units

Instrument flow rates	
MSS	3 x 4 lpm
LII	4 x 5 lpm
Excess	18 lpm
Total	50 lpm

Data for the pre-test comparison conducted on the 2nd August 2013, is given below in Figure 33. As can be seen there is excellent agreement between all 6 mass analysers independent of their instrument type, with a standard deviation in measurement of 4% compared to the average of all 6 analysers, with the two types of analysers overlying each other, particularly at higher mass concentrations. This illustrated that all of the analysers were functioning as expected after being transported back to Zurich from NRC Canada.

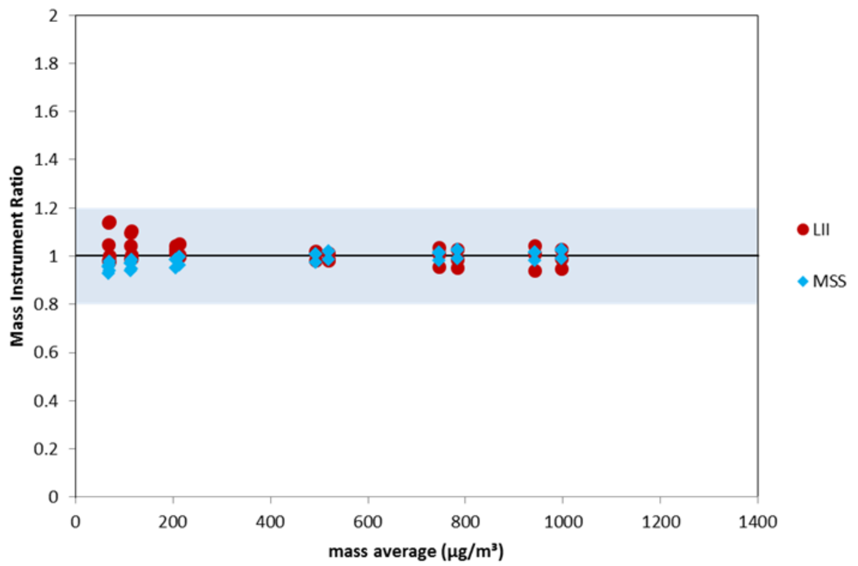


Figure 33 Pre-test mass analyser laboratory inter comparison conducted at SR Technics 2nd August 2013

To confirm that all of the analysers were still in good agreement following the three way inter comparison testing an additional post test laboratory comparison was made on the 6th August 2013. The data from this inter comparison is given below in Figure 34.

Retrospectively of the test campaign, it was found that inadvertently, the calibration factor on the North American MSS instrument was adjusted on the morning of 5th August 2013 prior to the engine test. It is thought this likely occurred during the pre-experiment checklist procedures, in performing the span check. AVL investigated, and determined that applying a factor of 0.891 to the results would return the data to the original calibration value, as such this factor was applied to the post-test mass comparison data and to the engine data for the North American MSS on the 5th August 2013.

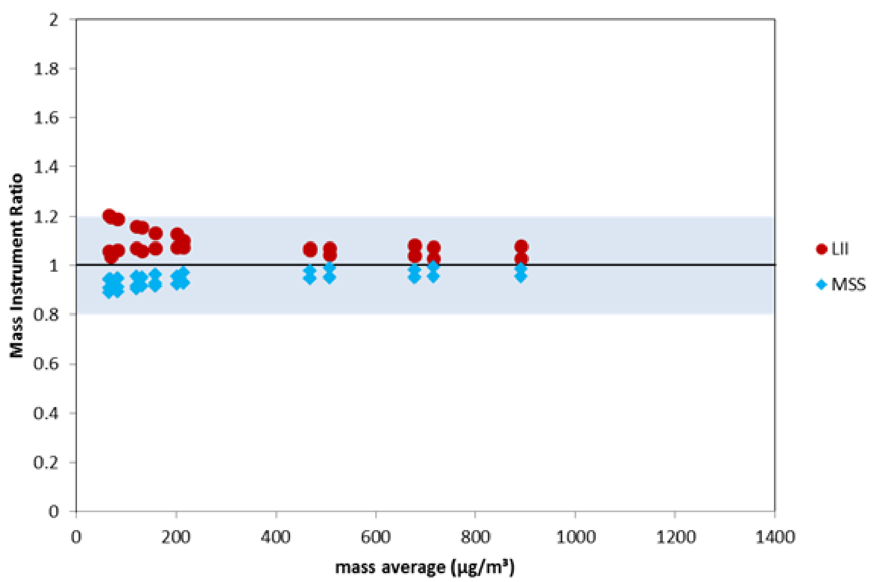


Figure 34 Post-test mass analyser laboratory inter comparison conducted at SR Technics 6th August 2013

It can be seen that the standard deviation has increased to 11% during the 4 days between comparisons; also it seems that there has been a distinct grouping of the two types of mass analyser with the LII typically reading slightly higher than the MSS units. It should also be noted that the North American LII is absent from this data set owing to the finding (Post-test) of a leak in the North American LII unit, this resulted in the instrument reading 20-30% low in comparison to EU/EASA and Swiss LII's.

A leak was identified in the sampling system prior to the mini-cast comparison by the LII (measurement spikes observed when should be none during zero check), however, despite a sustained search for the leak in the sampling system setup, the leak source could not be found and due to time constraints the mini-cast post-test comparison occurred with awareness of a leak in the North American LII dataset. It was subsequently found that the leak occurred inside the North American LII instrument, on an O-ring that had come loose on the measurement volume window of the North American LII, and had likely occurred during the pre-experiment checklist procedures, when performing a visual check of the cleanliness of the internal windows. On discussion with the instrument manufacturer Artium, they suggested this design has already been revised, thus should not occur in newer models of the LII-300 (Note that both the EU/EASA and Swiss LII's have the new seal design already).

In summary it is observed that there appears to have been a small change observed in the spread of data seen for the 6 reference mass instruments between the two laboratory tests performed before and after the three way system inter comparison. As such the measured standard deviation increased from 4-11% whilst it appeared that there seemed to be a distinct grouping of analyser type in the post test experiment, with the LII units reading higher than the comparative MSS units. However, even with this drift in agreement it should be noted that the overall agreement of both tests are within +/- 16% uncertainty associated with NIOSH 5040 EC/OC method.

6.5 EU/EASA Mobile Reference System Conformance

6.5.1 AIR 6241 System Set-up Compliance

A completed modified version of the most recent (version 6) SAE E31 AIR 6241 PMTG compliance tool is presented for the entire system, of the EU/EASA reference system in Table 10 to

Table 13.

Table 10 AIR 6241 Compliance check for Entire system (Chapter 4.1.1)

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	Max 26.83m from inlet 3PTS - furthest Analyser
			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	not EU/EASA reference issue
			Residence times	theoretically calculated all	not EU/EASA 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

Table 11 AIR 6241 Compliance check for Collection Section (Chapter 4.1.2)

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	OEM installation
			Material	conductive, grounded, non-reacting material	OEM installation
			Number of Sampling Locations	≥12 locations	OEM installation
			Total orifice area (multi-orifices probe)	at least 80% of the dynamic head pressure drop through the probe assembly is taken at the orifices	OEM installation
			Multiple sampling orifices	of equal diameter	OEM installation
4.1.2.2	2PTS	Probe exit to splitter1 inlet	Sample Temperature	maintained ≥418K if active cooling is used	OEM installation
			Material	• Stainless Steel • carbon-loaded PTFE • or other non-reactive materials	OEM installation
			Inner Diameter (ID)	4 to 8.5mm	OEM installation
			Sampling line Temperature	• 433±15K (160 ± 15°C) • except for the distance required to cool the gas from the exhaust	OEM installation
4.1.2	1PTS & 2PTS	Probe inlet to splitter 1 inlet	Target residence time	≤ 3s through the collection section at low engine power conditions	OEM installation
			Length	≤ 8m	OEM installation

Table 12 AIR 6241 Compliance check for Transfer Section (Chapter 4.1.3)

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	yes

				time in the Collection section	
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	$(D_{16}/D_{84})^{0.5} \leq 1.25$	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

Table 13 AIR 6241 Compliance check for Measurement Section (Chapter 4.1.4)

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

6.5.2 Non-Volatile Mass instrument & Calibration Compliance

A completed modified version of the most recent (version 6) SAE E31 AIR 6241 PMTG compliance tool is presented for the mass measurement instrument, of the EU/EASA reference system in Table 14 & Table 15.

Table 14 AIR 6241 Compliance check for nvPM mass instrument (Chapter 5)

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

Table 15 Compliance check for nvPM mass instrument calibration (Chapter 5.2)

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	

6.5.3 Non-Volatile Number Instrument & Calibration Compliance

A completed modified version of the most recent (version 6) SAE E31 AIR 6241 PMTG compliance tool is presented for the mass measurement instrument, of the EU/EASA reference system in Table 16 & Table 17.

Table 16 Compliance check for nvPM number instrument (Chapter 6)

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 10000p/cm3
			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		1 year old
			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 and AVL presentation
		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 against a traceable standard	yes see cal cert
			Readability	≥ 0.1 particles/cm^3 at concentrations <100 particles/cm^3	yes
			Response	linear	can't be checked
			Mode	photometric mode not allowed	10000p/cm3
			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	?

Table 17 Compliance check for nvPM number instrument calibration (Chapter 6)

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	

6.6 Sampling System Transportation

The design of the EU/EASA mobile reference sampling system was done to ensure when shipped to SR Technics that the installation would run as smoothly as possible. As explained earlier the design concept was to enable the entire system to be transported in one ‘standard’ van. As such the final system was fitted into 4 nominally identical 19” shock mounted ‘flight cases’ as described in section 6.3.10.

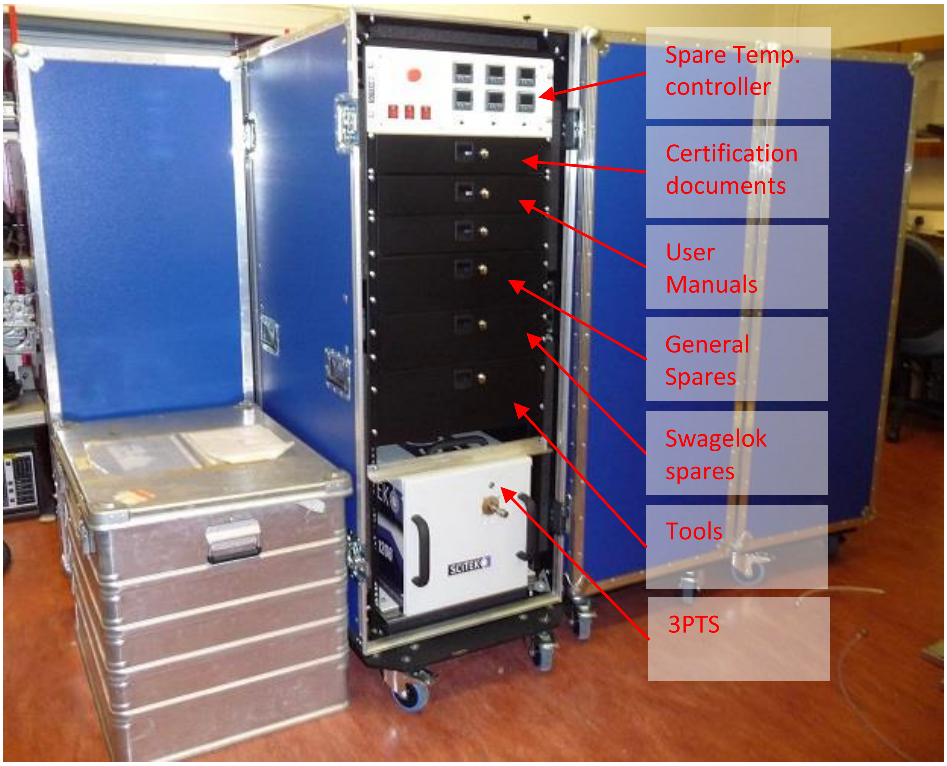


Figure 35 EU/EASA Mobile Reference System Shipping cases

As discussed earlier 3 of the cases contained all of the gas transfer, distribution and PM/gas measurement equipment, with the fourth housing the 3PTS hardware for shipment along with a spare 3 channel temperature controller, and 6 sliding lockable drawers containing all of the required certification and documentation, user manuals, spares and tools required to set up and operate the reference system at a remote location.

A fifth shipping case was also required which was used to ship all of the heated lines (4PTS, GTS, 2PTSa) and umbilical power and control lines required for the remote operation of 3PTS.

7. Task 3b: Cross-Validation of multiple ARP compliant systems at SR Technics

7.1 Introduction

The SAMPLE III consortium, Empa and MS&T used EASA, Swiss domestic aviation fuel tax, TC and FAA funding respectively to facilitate a three way inter comparison of three AIR 6241 compliant reference systems, namely; the EU/EASA mobile reference, the Swiss fixed reference and the North American mobile reference systems. In conjunction with these studies NRC with TC funding also investigated potential mass measurement on the Empa undiluted Annex 16 (GTS) exhaust line.

An experimental programme including the SAMPLE III programme was developed (APRIDE 5). This body of work included performing:

- single system tests with a 'certification-like' multipoint cruciform probe (EU/EASA and Swiss)
- 2-way system inter comparisons (Swiss / EU/EASA & Swiss / North American), utilising both the multipoint cruciform probe and single point probe utilised in previous studies (SAMPLE III SC02)
- 3-way system inter comparison (Swiss / EU/EASA / North American) utilising the single point probe).

Within this report only tests including the EU/EASA mobile reference system will be discussed, with the overriding objective of the tests being to provide data to help determine the overall measurement system variation (non volatile particle mass and number) of the currently proposed ARP methodology, along with an assessment of the operability of compliant systems. However, other SAE E31 potential 'roadblocks' and 'technical gaps' were also investigated during this study including non volatile PM variability, diluent composition sensitivity, dilution factor sensitivity, non-volatile PM stabilisation sensitivity and real time secondary dilution factor appraisal.

7.2 Experiment Overview

The data published here was taken at the SR Technics test cell, Zurich Switzerland, hence relevant descriptions of the facility are presented in the following sections.

7.2.1 SR Technics Facility Description

7.2.1.1 *Sampling Probe (1PTS)*

Two types of sampling probe were utilised during the test campaign. A traversable single point probe (identical to that used and described in SAMPLEIII SC02) and a fixed multipoint probe.

A photograph of the probe inlet and the traversable probe support are given below in Figure 36.

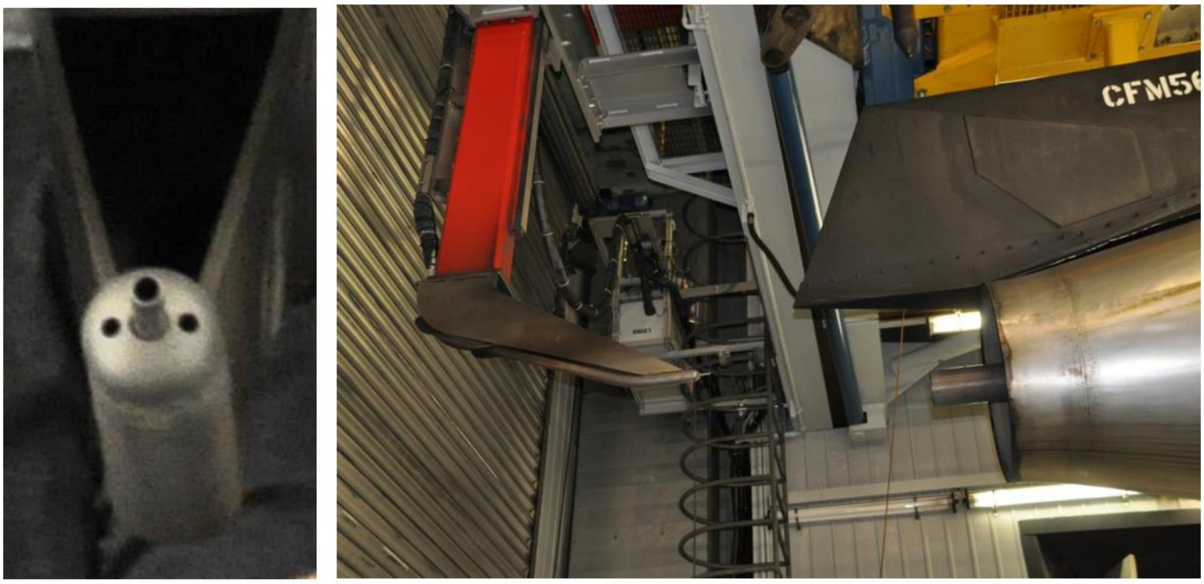


Figure 36 (a&b) FOCA 8mm single point probe front and side views respectively mounted in SR Technics test bed

The probe is an 8mm ID stainless steel, single point sampling probe, which is sheathed with a 25mm sleeve with 2 inlet holes which allow hot exhaust gases to flow past the probe sample line ensuring it does not cool below 160ºC, the probe sample line is made from 10mm OD (8mm ID) stainless steel line and is approximately 1m in length before coupling with the primary sampling line (2PTS). As explained previously, the probe can be traversed in the vertical plane on the centre line of the engine generally from below the centreline of the engine through the exhaust and out of the top of the exhaust stream.

It should be noted that this traversable single point probe does not meet with the specifications of AIR6241 for a number of reasons as discussed in SAMPLEIII SC02. For this reason it should be noted that all single point probe data published in this report can and should only be used to assess the performance of the sampling systems under investigation and is not representative of the engines being sampled.

The multipoint probe was designed and manufactured under the auspices of FOCA to acquire a representative sample from the dedicated lease engine. Due to proprietary reasons the detailed design of this probe cannot be published. The probe was manufactured from Inconel in a cruciform configuration with 4 arms which afforded the ability to sample from up to 24 orifii. The single orifice geometry was located at the same location as when the engine was originally certified by GE. The samples from all the orifii were ganged together and this ganged sample was sheathed by hot exhaust gases to help maintain the temperature of the sample to ensure it did not cool below 160ºC. The multipoint probe was fixed to the same (red) traversable girder in Figure 36. The girder was mechanically bolted in to position to prevent any vertical movement. The ganged sample line then attached to the same 2PTS section as used for the single point probe.

Throughout the 3-way system comparison the single point probe was utilised, as there were concerns that the multipoint probe construction integrity could fail at some stage prior to the certification-like test planned later on in the campaign (organised by the Swiss representation). In addition the larger inlet probe area (than the combined multipoint orifii in the certification configuration) helped to deliver a higher inlet pressure at the primary diluter of the three systems.

The multipoint probe was utilised during the two-way comparison (between the EU/EASA and Swiss systems) and when the EU/EASA system was being operated solely. For these two experiments the probe geometry (12 x orifii 'open') was identical to the certification-like tests performed by solely the Swiss system. Therefore samples obtained for these two experiments could be described as representative of the CFM56-7B26/3 engine.

7.2.1.2 *Primary Sample line (2PTS & 2PTSa)*

This section of the sampling system is common to all sampling systems. This section was initially 6m in length, and constructed from 10mm OD (8mm ID) bendable stainless steel pipe. The line is electrically trace heated and insulated to ensure the sample does not drop below 160ºC.

Whilst sampling with the single point probe, this length of line (plus 2PTSa) was AIR6241 compliant. However, as the multipoint probe assembly was of longer construction (in order to achieve the probe orifii being close to the engine exhaust plane), the possibility of a shorter heated line between the probe assembly and 2PTSa splitter would assist ensuring that this sampling section was AIR6241 compliant.

The 2PTS heated sample line was replaced by Empa with a shorter new section (length 5m) which was of identical construction. An engine piggyback test was used to condition this new section (as specified by AIR6241) prior to data being obtained for nvPM assessment.

The authors note that the heated sample lines used for 2PTSa (additional section to AIR6241 which is required when comparison testing of more than one system occurs), are described in section 6.3.3.

7.2.2 EU/EASA Mobile Reference System installation

7.2.2.1 *Reference System Location*

Careful consideration of the installation of the of the EU/EASA reference system was required based upon the knowledge gained during installation and operation of the sampling systems in SAMPLE SC02. During the SC02 test campaign a large amount of manpower was spent installing and de-rigging the system, due to confined installation space. In addition as there is no air conditioning, the ambient temperature for the instrumentation could increase above operating limits (>35˚C).

Several locations were considered for the EU/EASA reference system each of which is discussed with associated advantages and disadvantages in Table 18.

Table 18 Possible locations for positioning EU/EASA reference system at SR Technics

System installation location	Advantages	Disadvantages
In the corridor next to the Swiss system (same location as SAMPLEIII SC02)	Closest location to probe and therefore no problem with sample line length, Availability of HEPA filtered air, electricity and exhaust/dump line,	Confined space, Difficult installation, Possible overheating of instrumentation
In disused engine test cell on opposite side of corridor to in-use test cell	Plenty of available space, Completely un-obstructive to SR Technics test-bed operations	Require HEPA filtered air, electricity, exhaust line, More complex installation of sampling system under walls Disused test cell full of scrap parts that need to be stored elsewhere
Outside in-use test cell next to the fuel bunker	Plenty of available space, Completely un-obstructive to SR Technics test-bed operations	New holes need to be drilled in test-bed wall, 25m sample line length distance is tight, Require HEPA filtered air, electricity, exhaust line,
In hallway next to internal engine test cell doors	Plenty of available space Compressed air and electricity availability	Several walkways need to be crossed, Possible obstruction to SR Technics operation 25m sample line length distance is tight, Require exhaust line,

The hallway location was chosen as the installation location and the installation setup of all three reference systems is shown below in Figure 37. Measurements, performed by SR Technics, showed that the sample line length would be long enough to reach both the EU/EASA and North American reference systems. Floor covers were built by SR Technics to cover where the heated line crossed walkways (brown squares) and a pipe was installed to remove all the exhaust gases. In addition, direct phone lines were provided and installed by Empa between the Swiss system, EU/EASA & North American systems, and control room. This allowed good communication between the engine operators and all three sampling teams during engine testing.

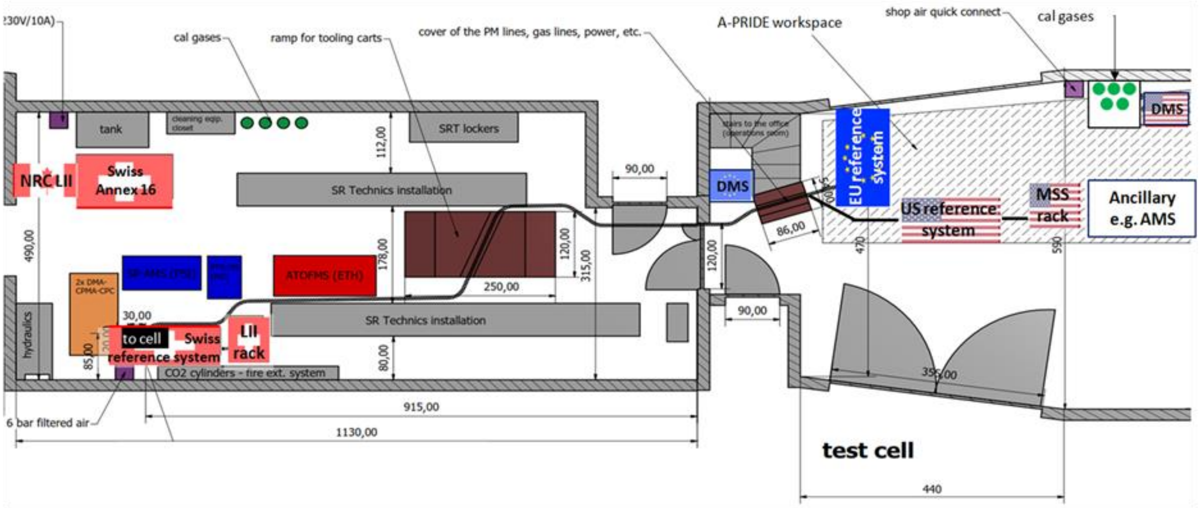


Figure 37 Schematic representation of location of reference systems at SR Technics (Figure adapted from Empa drawing)

A photograph showing the EU/EASA mobile reference system in the hall way next to the engine test cell doors is given below in Figure 38.

Figure 38 Photograph of EU/EASA Mobile Reference System location next to SR Technics Test Cell

7.2.2.2 *Reference System Operability*

The EU/EASA reference system was operated in accordance with AIR6241 throughout the engine testing. A completed modified version of the most recent (version 6) SAE E31 AIR 6241 PMTG compliance tool is presented for the entire system, for the operation of the

EU/EASA reference (note also includes calibration) in A-PRIDE 5 and is shown below in Table 19 to Table 21.

Table 19 AIR 6241 Compliance check for Sampling Section Operation

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, perfomed by holding a vacuum at 0.65 bara (with probe inlets blanked)
			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, perfomed by holding a vacuum at 0.65 bara (with probe inlets blanked)
	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 PTS section or measurement instrument shall be replaced	Yes, Mass passed, Number passed at all VPR dilution settings with limit at < 1p/cm3 not 0.5 p/cm3 due to VPR inlet leak (see report)
	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	Not performed, only optional

				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)	
	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 the semi-dried raw gas temperature • If this dewpoint limit is exceeded, the sample shall be dried and corrected to CO2 wet	Diluted sample not dried, measured wet

Table 20 AIR 6241 Compliance check for Mass measurement Operation

AIR 6241 Chapter	AIR 6241 Chapter	Component	Operation Criteria	Requirements	Compliance check
AIR 6241 Mass Measurement Operation					
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 (by Empa)
			nvPM mass Emission Index	calculated from mass concentrations, fuel composition and CO_2 concentration (after Diluter 1)	Yes

Table 21 AIR 6241 Compliance check for Number measurement Operation

	AIR 6241 Chapter	Component	Operation criteria	Requirements	Compliance check
	AIR 6241 Number measurement operation				
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 not 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, 2 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	Yes as per AVL calibration.

				• measured upstream and downstream of VPR components with CPC • CPC with ≥ 90% counting efficiency for 15nm particles	Calibration performed with CS at 300 °C therefore pre-test comparison performed vs APC calibrated at 350 °C
			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)	Yes, both options
	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, 2 months before emissions test (no major maintenance performed)
	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	

7.2.3 Test relevant Certification Records

7.2.3.1 *Zero & Span Gases*

A summary of all of the Zero and span gases used in the SR Technics test campaign is given below in Table 22, with copies of the certificates presented in Appendix 10.4

Table 22 Summary of Span & Zero Gases used at SR Technics

Description	Composition	Accuracy	Analysis Cert.	Expiry Date
Zero Air	20% O_2 (balance N_2)	N5.5 (N6.0)	Carbagas 1356379	26/06/2015
Raw CO2 Span	4.49% (balance air)	±1%	Carbagas 1356344	28/06/2015
1° Diluter CO_2 Span	0.4495% (balance air)	±1%	Carbagas 1356347	01/07/2015
2° Diluter CO2 Span (H)	75.1ppm (balance air)	±2%	Carbagas 1356346	03/07/2015
2° Diluter CO2 Span (M)	50.1ppm (balance air)	±2%	Carbagas 1356345	03/07/2015
2° Diluter CO2 Span (L)	25.2ppm (balance air)	±2%	Carbagas 1356343	03/07/2015

7.2.3.2 *Fuel Analysis*

SR Technics adjusted their fuelling schedule such as to ensure the fuel composition stayed as constant as possible during the campaign. Empa performed a fuel analysis of the fuel in the tank supplying the engine test cell numerous times during the test campaign. A summary of the results with the Annex 16 specifications are presented below in Table 23 and the individual test certificates are presented in Appendix 10.4.

Table 23 Summary of measured fuel specifications for fuel used at SR Technics (Table adapted from Empa)

Parameter	Unit	Annex 16 LOW	Annex 16 HIGH	29/07/13	02/08/13	05/08/13	05/08/13	12/08/13	17/08/13	25/08/13
Aromatics	% (V/V)	15	23	17.7	17.7	17.4	17.4	18	17.7	17.5
Sulphur, total	% (m/m)	0	0.3	0.053	0.033	0.039	0.039	0.039	0.042	0.042
Initial boiling point	°C	NA	NA	155	151	155	155	151	149	153
10 Vol % recovered	°C	155	201	169	168	168	168	168	167	169
20 Vol % recovered	°C	NA	NA	175	174	174	174	174	173	174
50 Vol % recovered	°C	NA	NA	193	193	193	193	193	193	193
90 Vol % recovered	°C	NA	NA	236	236	236	236	235	234	235
End point	°C	235	285	265	265	265	265	261	263	264
Residue	% (V/V)	NA	NA	1.10	1.10	1.10	1.10	1.10	1.10	1.20
Loss	% (V/V)	NA	NA	0.5	0.6	0.8	0.8	0.7	0.4	0.6
Density at 15 °C	kg/m³	780	820	797.6	797.7	797.8	797.8	797.8	797.8	797.2
Viscosity at -20 °C	mm²/s	2.5	6.5	3.591	3.618	3.598	3.598	3.596	3.599	3.618
Specific energy, net	MJ/kg	42.86	43.5	43.3	43.3	43.3	43.3	43.3	43.3	43.3
Smoke point	mm	20	28	21	21	21	21	21	22	22
Naphthalenes	% (V/V)	1	3.5	0.68	0.72	0.71	0.71	0.71	0.74	0.70
Hydrogen	% (m/m)	13.4	14.3	14.18	14.18	14.28	14.28	14.04	13.96	13.76
H/C ratio (calculated)	NA	1.84	1.99	1.97	1.97	1.98	1.98	1.94	1.93	1.90

As can be seen the fuel composition remained very constant across the entire test campaign, which allows other variables such as ambient effects to be investigated independently of fuel related differences in PM.

It is also seen that with the exception of Naphthalenes the fuel meets the Annex 16 fuel specifications as highlighted by those rows marked green in Table 23.

7.2.4 Dedicated Lease Engine

The lease engine was type CFM56-7B and is flying in-service on a high number of aircraft in the world. The most recent variant is the /3 variant, commercialised as "tech insertion". The "26 rating" was selected in order to cover most of the thrust range of the CFM56-7B family.

The chosen leased engine (shown in Figure 39) was carefully selected by SR Technics based on experienced knowledge of performance data recorded from such models. The selected engine was shown to meet the upper end of the performance range, similar to a completely overhauled engine.

SR Technics performed an engine in-coming performance run, a mid-campaign performance run prior to the emission certification-like test and an end-of-lease performance run. All three runs confirmed good and stable performance of the selected engine. Additionally, performance data at maximum continuous operation with and without the fixed emissions probe was compared and no significant influence on the impairment of engine performance was observed.

Figure 39 CFM56-7B26/3 mounted in SR Technics test Cell

7.2.5 Swiss Fixed Reference System Description

The Swiss Fixed mobile reference system is permanently installed at SR Technics and is maintained and operated by Empa. As a reference system it is AIR6241 compliant, with additional Gaseous measurement devices for measurement of CO (dried), NOx (dried), and THC's.

The only notable differences to the EU/EASA system are that the heated line (4PTS) is constructed from 2 off 12m (8mm ID) lines connected with a heated section of approximately 15cm. The Swiss compliant system uses an AVL MSS as its primary mass analyser and has an Artium LII on the spill line located in 5PTS with a 3m heated line connecting the device, and the GTS transfer line is made using a smaller ID of 6mm which enables the residence time to be reduced (for similar GTS sample flow rates used in the EU/EASA system) in transferring the sample, and therefore is within the Annex 16 specifications for residence time.

For the comparison tests discussed in this report the Swiss system also had an additional Artium LII-300 (operated by NRC Canada) fixed on the GTS line which was hence, sampling raw exhaust. However this data is not discussed in detail at this time.

A photograph of the Swiss 5PTS and PM mass and number instrumentation installation is shown below in Figure 40 (note that the secondary mass instrument, LII, is not shown in this photograph).

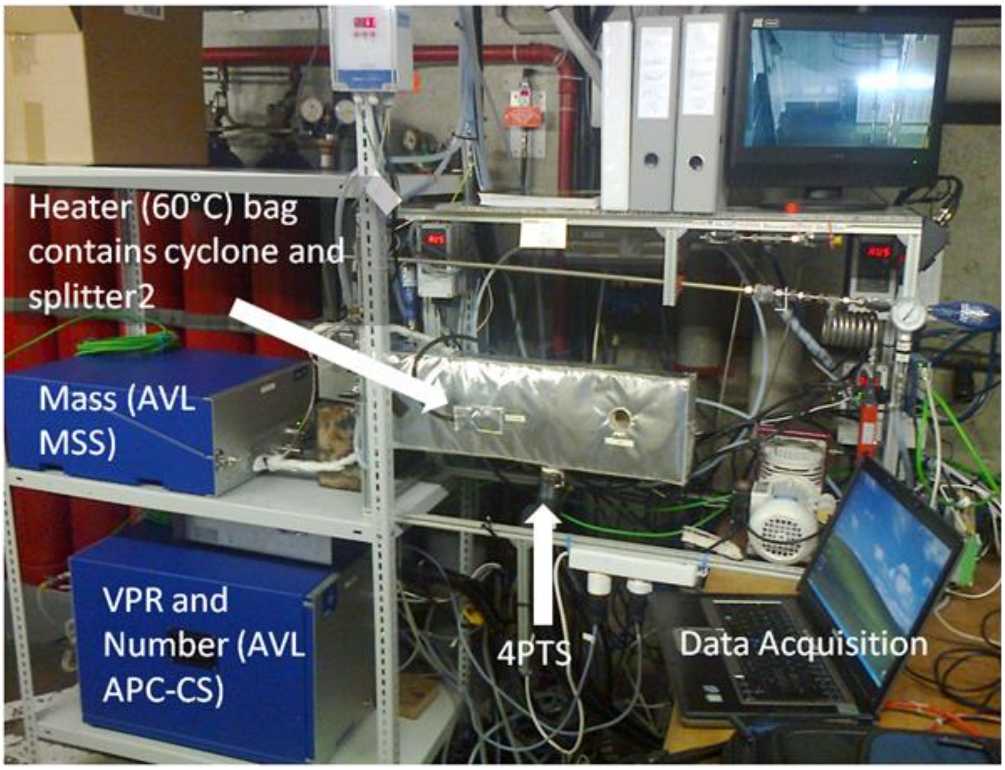


Figure 40 Swiss nvPM reference system setup

7.2.6 North American Mobile Reference System Description

The North American mobile system is also a fully compliant reference system, and operates with similar primary measurement instruments to that of the EU/EASA mobile reference system namely; AVL APC and Artium LII-300, for PM number and PM mass, respectively. The North American reference system also runs a secondary mass analyser, AVL MSS, from the 5PTS dump line utilising a 3m heated line. The North American system currently does not run a raw exhaust CO_2 analyser on its GTS, but uses the raw value measured by the comparative system being tested (for all DF1 data in this report the EU/EASA raw CO_2 data was utilised for the North American system), which will reduce the measurement uncertainty between the two systems under test as the associated gaseous uncertainties are not included in their comparison. However, the system has a make-up pump and GTS equivalent line to ensure all flows are matched and within AIR 6241 specification.

Additional ancillary instrumentation was also added onto the North American 5PTS dump line consisting of a DMS500 fast mobility spectrometer to measure PM size distributions, an Aerosol Mass Spectrometer (AMS) for PM chemical composition information, and a Cavity

Attenuated Phase Shift (CAPS) PM extinction monitor to obtain another measure of nvPM mass.

A photograph of the North American 5PTS and PM mass and number instrumentation installation is shown below in Figure 41.

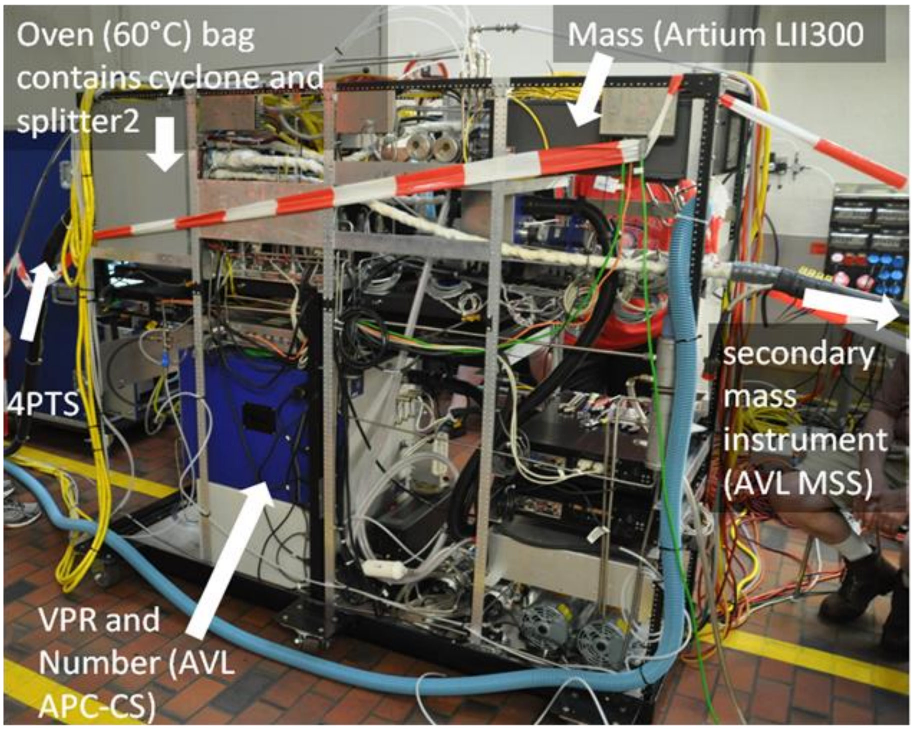


Figure 41 North American nvPM reference system setup

Note that in data analysis figures, the North American system is labelled as 'US'.

7.2.7 Experimental Schedule

APRIDE 5 was a month long test campaign involving numerous test partners thus, organisation and efficient use of the dedicated engine was crucial, as such there were numerous meetings and teleconferences aimed around scheduling of the experimental programme.

7.2.7.1 *Test Campaign Scheduling*

An overview of the SAE E31 relevant testing is presented below in

Table 24. The table details the engine being tested, the type of test namely dedicated, Piggyback or Laboratory, a description of the test being performed along with details about the probe and the reference systems being tested.

Table 24 SAMPLE IIISC03 (APRIDE 5) Test Schedule

Date	Engine	Test type	Test Description	Probe	AIR6241 compliant Systems		
					EU/ EASA	Swiss	North American
26/07/13	CFM56-7B26/3	D	Lease engine serial number and boroscope check by SR Technics	-	-	-	-
27/07/13	CFM56-7B26/3	D	Engine pre-lease performance run	-	-	-	-
28/07/13	CFM56-7B26/3	D	Mechanical check of multipoint probe, AFR check (4 x LTO points)	Multi (Tips 1,4,6)	x	x	
29/07/13	CFM56-7B26/3	D	AFR check (4 x LTO points) Dilution Factor sensitivity operation assessment	Multi (All 24 Tips)	x	x	
30/07/13	miniCAST	L	5-way Mass instrument inter-comparison (3 x LIIs and 2 x MSSs)		x	x	
31/07/13	CFM56-7B	P	Piggy back test to assess flow rate required for 3 systems	single	x	x	
	CFM56-5C	P	Piggy back test -MSS and LII Diluent composition comparison test (EU/EASA system on Nitrogen and then Synthetic Air)	single	x	x	
02/08/13	miniCAST	L	APC intercomparison – CS temp. 7-way Mass instrument inter-comparison (4 x LIIs and 3 x MSSs)		x	x	x
03/08/13	CFM56-7B26/3	D	3 way Intercomparisons– 1 x full matrix, 2 x subset matrix Diluent composition comparison N2 (Swiss & North American) vs. Synthetic Air (EU/EASA)	single	x	x	x
04/08/13	CFM56-7B26/3	D	3 way Intercomparison - Repeat testing 4 x subset matrix Dilution factor sensitivity test (2 x DF at 2 engine conditions)	single	x	x	x
05/08/13	CFM56-7B26/3	D	3 way Intercomparison MSS on Swiss system – 1 x subset matrix Engine trim balance performed by SR Technics	single	x	x	x
06/08/13	miniCAST	L	7-way Mass instrument inter-comparison (4 x LIIs and 3 x MSSs)		x	x	x
07/08/13	PW4168	P	New 2PTS line installed, Piggy back test to condition line	single		x	x
09/08/13	CFM56-7B24	P	Piggy back test on SR Technics customer engine	single		x	x
10/08/13	CFM56-7B26/3	D	AFR Check with multi-point probe using probe tips 2, 4, 6	Multi		x	x
11/08/13	CFM56-7B26/3	D	2 way Intercomparison Vertical traverse of engine exit	single		x	x
12/08/13	CFM56-7B26/3	D	2 way Intercomparison	single		x	x
	CFM56-7B26/3	D	Engine intermediate-lease performance run	-	-	-	-
17/08/13	CFM56-7B26/3	D	Certification-like (1 x curve)	multi		x	
18/08/13	CFM56-7B26/3	D	Certification-like test (2 x curve)	multi		x	
19/08/13	CFM56-7B26/3	D	Long (30 mins) test points	multi		x	
23/08/13	CFM56-7B24	P	Piggyback test to re-check EU/EASA system operability	single	x	x	
24/08/13	CFM56-7B26/3	D	2 way Intercomparison. PCRF variability study	multi	x	x	
25/08/13	CFM56-7B26/3	D	Certification-like test (1 x curve) Secondary dilution factor accuracy Dilution Factor sensitivity test	multi	x		
26/08/13	CFM56-7B26/3	D	Engine post-lease performance run	-	-	-	-

Test Type Key: Dedicated (D), Piggyback (P), Laboratory (L)

7.2.7.2 *ICAO Landing Take-Off cycle testing*

Aircraft turbofan and turbojet engines are regulated for local air quality emissions at airports (ICAO Annex 16, Vol.II). The regulated engine certified emissions are calculated using a Landing Take-off cycle (LTO) with a set period at each point in the cycle as shown in the Figure 42.

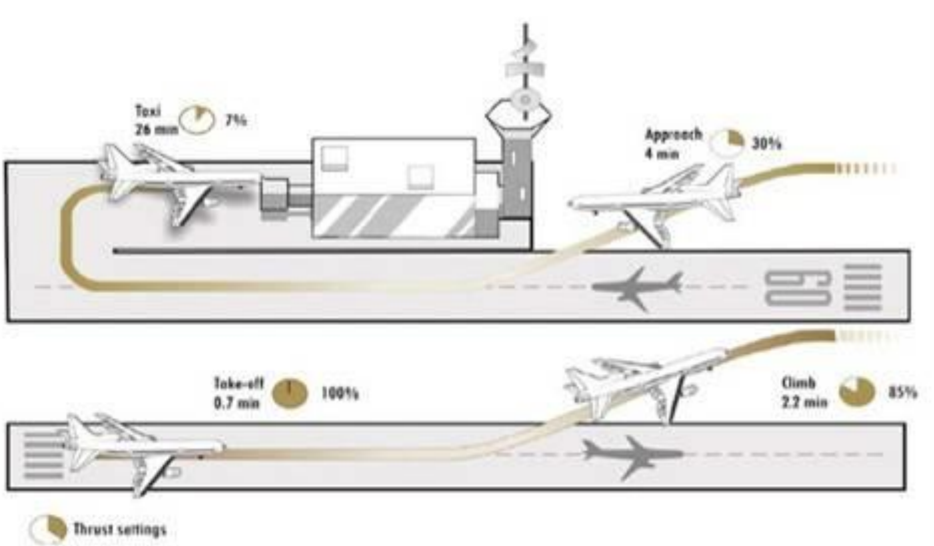


Figure 42 ICAO LTO Emissions Cycle

The LTO cycle contains four engine power conditions; Taxi (7%), Approach (30%), Climb (85%) and Take-off (100%), all at sea level (ISA) static thrust. To help the CAEP nvPM certification process, these engine conditions were chosen as a minimum for the dedicated engine test campaign, with the schedule described in more detail in the next section.

7.2.7.3 *Dedicated Engine Test Schedule*

The overall engine test matrix included an engine warm-up sequence including an engine 7% idle system operability check, followed by further warm-up step points and an engine test point sequence that started at the highest engine power condition and then stepped down in engine power to ground idle.

The full possible test matrix consisted of 12 test points. The engine power conditions for these 12 test points were set using the combustor inlet temperature T3 value, corresponding to sea level (ISA) static thrust. This is a common procedure for gaseous emission certification. It was decided to apply this engine setting variant accordingly for the PM measurements. As the ISA reference T3 settings are proprietary, only SR Technics had access to this information, to allow the test cell operators to set the engine power condition. This meant that with ambient conditions changing daily (or hourly), the engine T3 was kept constant for the selected test points.

It should be noted that as the ambient inlet air condition vary, comparative (same condition description) test points on different days were subject to the ambient variation on thrust and combustor inlet conditions. The 3-way system comparison tests were performed on hot days, leading to a significant reduction in measured thrust at a given T3 setting. In order to attempt to capture the high end of the engine thrust range it was decided to include a highest test point (Test Point 0) at maximum continuous operation limit of the engine (this only occurred from the 17th August onwards).

This difficulty in assessing comparative engine data for varying ambient conditions is discussed in Task 2.

Table 25 lists the full test matrix used during the measurement campaign. Each measurement test conducted used either the full test matrix or a subset of the 12 test points. Sampling duration at each test point was planned for 15 minutes, with at least 5 minutes allowance for engine stabilisation and around 10 minutes for sampling (if required). Actual nvPM test point data was obtained over a 30s period (as specified by AIR6241) after the engine PM signal was deemed stabilised by all system team leads.

In addition, as in conformance with AIR6241, cleanliness (equating to a PM system leak check) and ambient air checks were performed immediately prior to the start and upon the completion of each test, and gas analysers were calibrated within every hour on-test. However, there is inconsistency in the length of time required by AIR6241 for ambient (and zero) measurements (3 minutes) compared to engine measurements (30s).

Table 25 Available Power Conditions for Dedicated Engine Testing with CFM56-7B26/3 (Table adapted from Empa)

	Test Point	Ref FN at sea level(lb)	Remarks	Approx. Duration (mins)
Warm-up sequence	Warm up GI (3%)	764	Engine Shop Manual	5
	Warm up 15%	3945	Engine Shop Manual	5
	Check 7%	1841		5
	Warm up 65%	17045		5
Engine test points	0	-	Max Continuous	15
	1	26300	100% High	15
	2	25430	100% Low	15
	3	22956	85% High	15
	4	21671	85% Low	15
	5	17045	65%	15
	6	8158.8	30% High	15
	7	6792	30% Low	15
	8	5553	21%	15
	9	1866.3	7% High	15
	10	1626.6	7% Low	15
	11	1191.1	5%	15
	12	764	GI (3%)	15
Cool down sequence	GI (3%)	764		5

7.3 Data Analysis

As described earlier, the SAMPLE III consortium were involved in testing over two distinct test periods from the 3rd-5th August 2013 and the 24th-25th August 2013, thus these are the only results from the overall test campaign (APRIDE 5) that are described at this time.

During these test dates three types of testing were performed namely; (1) ‘Certification Like’ Single System Testing, (2) Two way Swiss Fixed & EU/EASA Mobile Reference System Inter-comparison & (3) Three Way Swiss Fixed, North American Mobile & EU/EASA Mobile Reference System inter-comparison. For type (3) testing, actual measured engine data (corrected by FOCA) was used for analysis in Task 2. For AIR6241 system operation and comparison analysis; type (1), (2) and (3) testing, engine target test points listed in Table 25 are used instead of actual proprietary or corrected engine data.

As such the data is processed and presented as three distinct blocks of work in the following sections to investigate operability and repeatability of nvPM measurements, along with determining reference system variability in PM measurement.

7.3.1 Data Analysis Procedure

In order to allow data analysis, all data from each of the measurement analysers is recorded real time throughout the engine run. The raw data files are presented graphically for nvPM mass, nvPM number and Gaseous emissions in Figure 43 (a-c).

As can be seen in Figure 43 on this particular engine test after completing an engine warm up cycle, four down curve runs where investigated at 5 different engine target powers namely; 100%, 85%, 65%, 30% & 7% which cover the four LTO T3 settings with an additional pseudo cruise test point (65%). It can be seen that there are step changes in both PM and gaseous emissions measured with changes in engine power, observed on all three reference systems simultaneously, which confirms the time stamping of each system is correct.

However, it can be observed that upon the engine reaching a new power condition it takes a period of time before the PM reaches a stable value. Further in-depth analysis of this stabilisation time is discussed in section 7.3.9. To ensure that comparative data for each of the reference systems representative of the engine power condition are taken simultaneously, agreement is sought from each team lead that the PM data on their system is steady before a test point is called. At this stage the test point is recorded with a start and end time, so PM stable data is recorded and analysed for all measurement systems for the same period of time.

Due to the multiple dilution stages in 3PTS (DF1) and within the nvPM number system (DF2), the raw data measured by the PM analysers in the reference systems are not representative of the raw exhaust leaving the engine. It is noted that due to slight variations in sample line geometry, system engineering and diluent supply pressure, each reference system runs at a different dilution factor. Thus in order to compare the PM instruments from each system it is necessary to multiply the measured value by the total dilution factor to get back to a value representative of that entering 3PTS. Identical comparisons could be performed using EI calculated data; however, by plotting mass or number concentration it makes it easier to interpret system comparative data. Note that for the dual or tri-comparison data presented, the raw sample CO_2 data has not been corrected for water on either the EU/EASA or Swiss system (the North American system does not have a raw analyser), however, as both raw CO_2 samples are semi-dry (chilled to ~2 to 5°C), for comparative PM instrument analysis there is no impact on the analysis and conclusions. For EI comparative data the diluted (already wet) CO_2 PM specific system value was utilised. As specified earlier, as the single point probe was used to sample for the 3-way comparison the absolute data is not representative in any case.

In order to generate nvPM concentrations suitable for certification-like (representative) comparison/presentation the numbers are normalised to fuel burn and expressed as an Emission Index (EI) giving PM loadings per mass of fuel burned, as described in AIR 6241 using the diluted CO_2 (not dried) value.

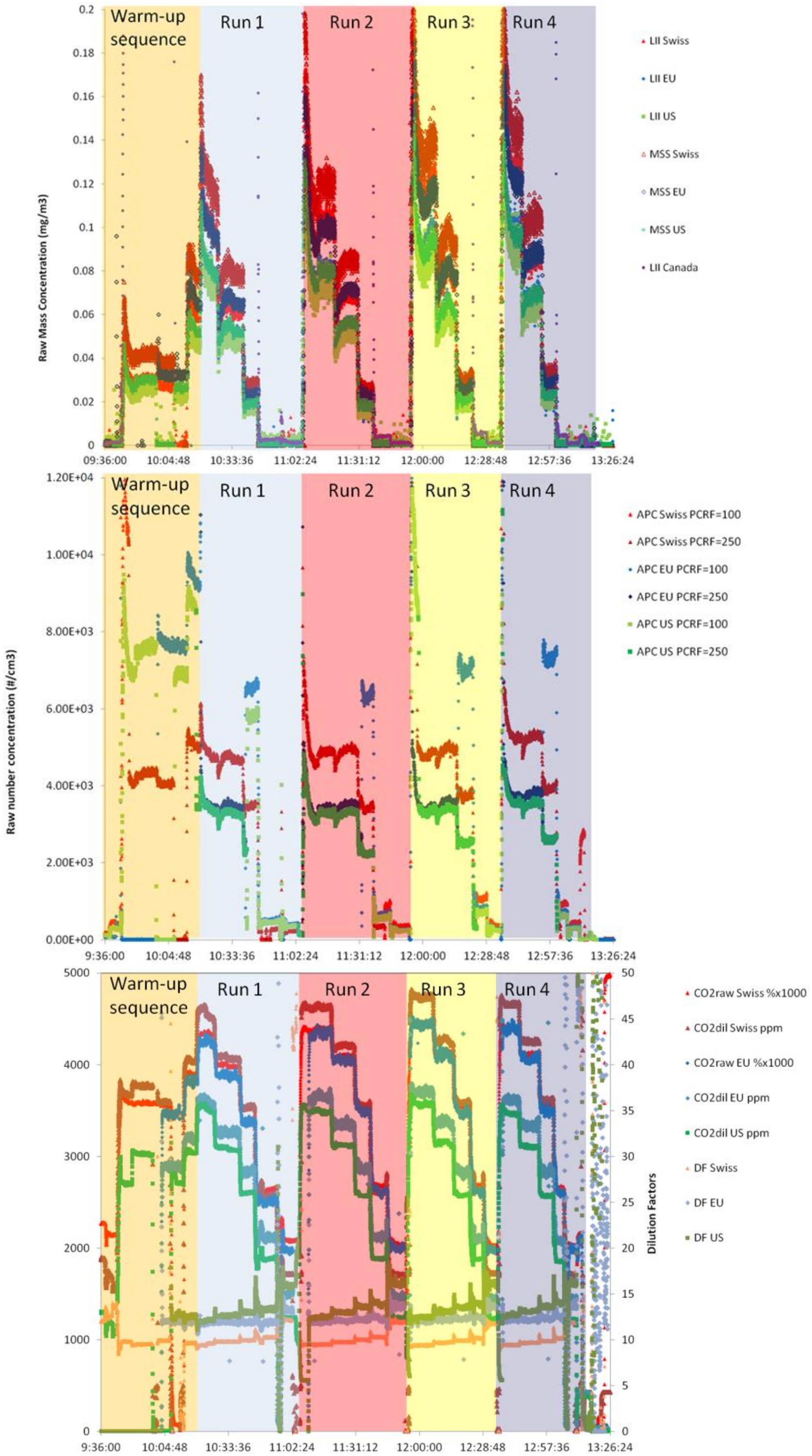


Figure 43 (a-c) Indication of typical Engine Test sequence showing multiple reference system raw data outputs for mass, number and gaseous respectively

7.3.2 Single System Testing using certification-like probe

As can be seen in Table 24 the EU/EASA mobile reference system conducted a full days certification like single system test on the 25th August 2013 using the multipoint certification-like probe, it should be noted that during this test run the ambient temperature was considerably cooler than previous test days in APRIDE 5, so the effective thrust levels would be considerably higher than previous data (for example 85% on a cold day is more comparable to 100% on a hot day based on a T3 setting). This test run was designed to further investigate SAE E31 PM ARP 'outstanding issues' which are described later in sections 7.3.5 to 7.3.10. As such actual measured engine proprietary data were not needed for this purpose.

However, in conducting the aforementioned studies it is possible to plot emission indices for mass and number which may be used, subject to possible future ambient effect corrections.

During the 25th August 2013 target test points were taken for various power levels namely; Ground Idle 3% (GI), 7%, 65%, 85%(HI), 100%(HI) and Max Continuous (MC). As such the measured EI values are presented in the following sections for both number and mass along with size distributions. As specified earlier, actual measured engine settings and ambient conditions are not taken into account.

7.3.2.1 *Non Volatile Number Measurements*

Measured EI non volatile PM values measured with a certification-like probe by the EU/EASA mobile reference system are presented below in Figure 44.

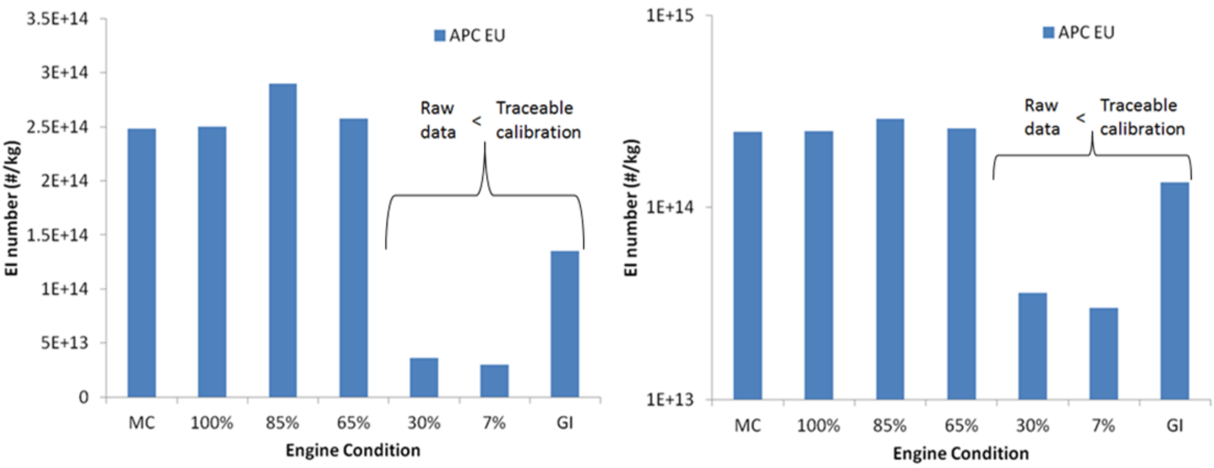


Figure 44 Linear and Log scaled Certification Like EI non volatile PM number data for EU/EASA mobile reference system from CFM56-7B26/3, multipoint probe, 25th August 2013

It is seen that the highest values of non-volatile PM number are witnessed at a climb like (85%) power rating, followed by cruise type (65%) power and the higher take-off (100%) and Max Continuous. The lower power conditions of approach (30%) and idle (7%) are then observed to have considerably lower EI number loadings with a further increase in number again witnessed for Ground Idle. This increase at GI is possibly due to the lower combustion efficiency at this power setting.

It is observed that both PCRF's of 100 and 250 were required to measure the nvPM number values, this was in order to keep the number counters' raw counts within the traceably calibrated range of 2000-10000 particles/cm^3. To achieve this aim the primary dilution factor had to be adjusted by controlling the spill valve, unfortunately for some low engine power conditions it was not possible to meet the AIR6241 specifications for both primary dilution factor (due to low inlet pressure at the dilutor) and number counter traceably calibrated range (due to low nvPM number signature at low engine powers). Hence these values are not included below in Figure 45, which shows variations in EI number witnessed dependant on how the system is operated within AIR 6241 specification i.e. with high primary dilution and low PCRF or with low primary dilution and high PCRF.

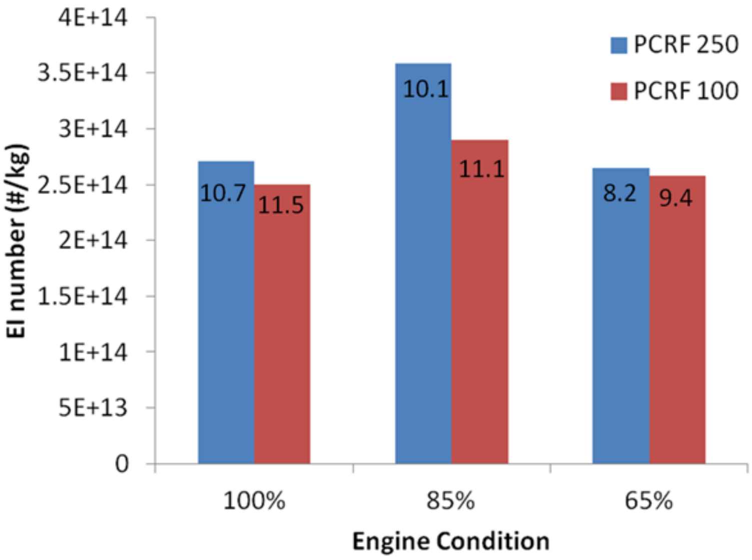


Figure 45 EI non volatile PM number data for EU/EASA mobile reference system at different PCRF from CFM56-7B26/3, certification-like multipoint probe, 25th August 2013 with primary dilution factor highlighted. Both PCRF data-points obtained on a single stable engine setting.

As can be seen for three of the power conditions it was possible to operate the APC within the AIR 6241 traceable calibrated range with a primary dilution factor also in specification. It is observed that in all three conditions observed that higher EI numbers were measured if using a lower primary dilution factor and higher PCRF of 250. It is unknown if the differences observed were due to DF1, PCRF (VPR DF2 setting) or slight engine variability (within a stable condition). However, with further observed data below in the two-way comparison (Figure 48) it is likely that the higher VPR dilution setting (PCRF 250) is the cause. For clarity, all the particle number data is corrected for VPR dilution via the gas dilution factor generated by the pre-test VPR dilution check (does not include the particle loss correction factor included in the PCRF).

7.3.2.2 *Non Volatile Mass Measurements*

Similarly EI mass data was generated during the EU/EASA mobile reference system testing with the certification-like probe and is presented on linear and log scales in Figure 46.

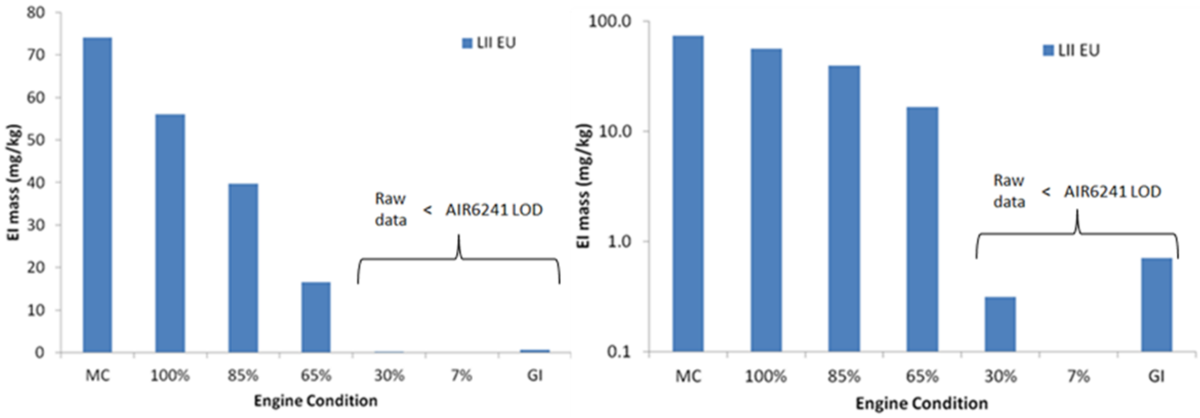


Figure 46 Linear and Log scaled Certification Like EI non volatile PM Mass data for EU/EASA mobile reference system from CFM56-7B26/3, multipoint probe, 25th August 2013

For the EI mass data it is observed that the loadings reduce with reducing power throughout the target LTO conditions with the additional cruise (65%) fitting into the trend. Again it is observed that an increase in EI mass to levels higher than those witnessed at approach is seen for Ground Idle (3%) cases. It should be noted that for engine conditions at 30% and below, the LII instrument was below the AIR6241 3xLOD specification for the mass instrument. However, the averaged (over 30s) LII data still produces a measurable signal at 30% and GI target conditions, but at 7% the signal was within the instrument noise (by averaging over a longer time period it may be possible to produce a measurable signal at 7%).

7.3.2.3 *PM Size Distribution Measurements*

During the certification type testing Empa operated a TSI FMPS on the size outlet of the EU/EASA mobile reference cyclone and secondary splitter oven (5PTS). The data of which is presented graphically in Figure 47.

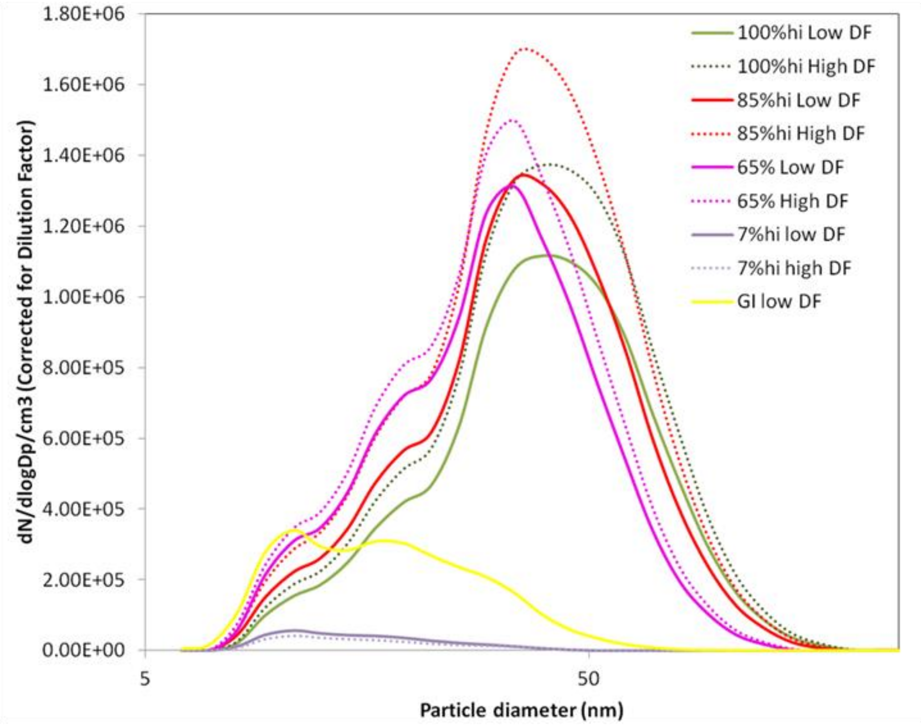


Figure 47 Total PM size distributions measured using TSI FMPS analyser, CFM56-7B26/3, multipoint probe, 25th August 2013. The high and low DF factors correspond to the values shown in Figure 79

It is observed that the size analyser seems to display a tri-modal distribution for all engine powers, which may imply that there is some volatile fraction condensing after the primary dilutor. This is not unexpected as there is no volatile removal device upstream of the FMPS, so volatiles will be measured if present. However, there could also be a trait of the FMPS instrument. It is again observed that the highest number concentrations are observed at 85% power, followed by 65% and 100% in agreement with the nvPM number data discussed earlier. It is noted that the GMD of the distribution seems to reduce with power, which would explain the increased mass loadings observed at the high power conditions at comparatively lower number concentrations.

The final observation is that the GI test point with low primary dilution seems to exhibit a very prominent volatile nucleation mode, which would possibly be expected at this very low power condition, this strengthens the argument in support of catalytic stripper technology requirement in the nvPM number measurement system. A similar peak is also prevalent in both the 7% idle cases.

7.3.3 Two way Swiss Fixed & EU/EASA Mobile Reference System Inter-comparison

The two way inter-comparison between the Swiss Fixed and EU/EASA Mobile reference system occurred on the 24th August 2013 using the multipoint probe as described in Table 24.

7.3.3.1 *Non Volatile Number Measurements*

During the two way inter-comparison the effect of the VPR DF2 (labelled PCRF) setting was again investigated. As such for a stable engine operating condition the PCRF of the AVL

APC was switched from 250 to 100 on both systems, then one system operated at PCRF 100 with the other switching to 250. Graphical data is presented for the study in Figure 48.

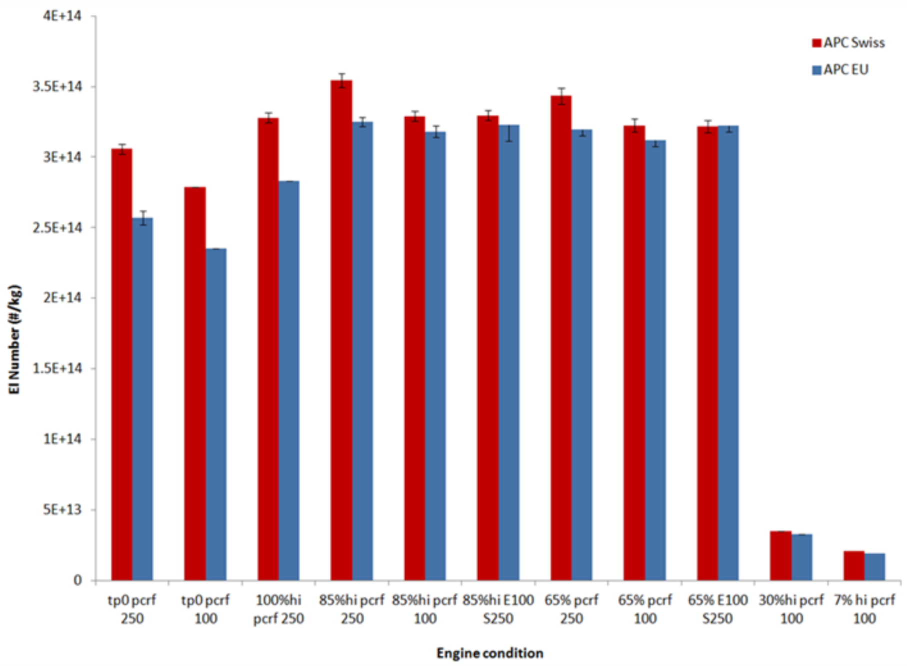


Figure 48 Two way inter-comparison EI Number measurements from CFM567B26/3, using multi probe, 24th August 2013

It is again observed that operating at a higher DF2 (PCRF 250) appears to give higher EI number values for both systems across all power conditions. It is also observed that the Swiss system measures higher EI number concentrations than the EU/EASA mobile system, in agreement with the pre-test comparison conducted using the mini-CAST soot generator discussed earlier in section 6.4.1.3. To allow the data to be compared more easily the two systems EI numbers are normalised against each other and presented in Figure 49.

As can be seen the majority of comparative points are within the greyed out 20% boundary that has been added to the graph. This boundary has been added by the authors as an expected uncertainty based on the estimated uncertainty budget calculated previously (SAMPLE III SC02) as between 18-22% dependant of the input variables. It is observed that typically the Swiss system is measuring 7-12% higher than the EU/EASA system which is comparable to that witnessed in the pre-test inter-comparison using the mini-CAST.

It is also observed that when both systems are operated at the same DF2 (PCRF setting) there appears to be a standard offset however, when the EU/EASA system was operated at a PCRF of 250 and the Swiss at a PCRF of 100 (data shown as green triangles) the two systems measure comparable values with the data being positioned on or around the unity line.

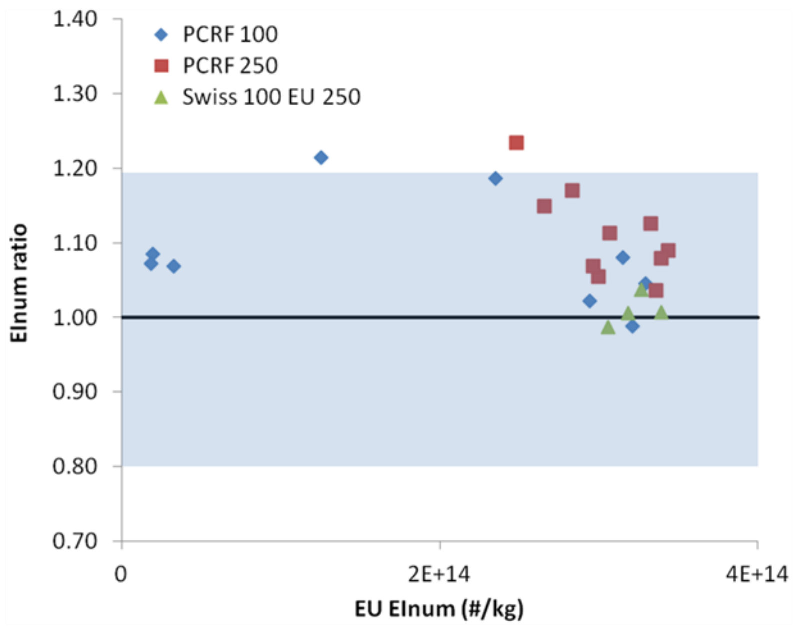


Figure 49 Effect of PCRF on AVL APC number count from CFM567B26/3, using multi probe, 24th August 2013

This data set again seems to demonstrate that the way a system is operated in terms of primary dilution factor and DF2 (PCRF setting) can subtly affect the resultant EI number measured. As running in either mode of high primary dilution/low DF2 or low primary dilution factor/high DF2 are both within specification of AIR 6241, the added uncertainty of operation mode (as chosen by the operator) needs to be further assessed. However at present it is noted that the majority of the variations lie within the theoretically calculated uncertainty of 18-22%.

7.3.3.2 *Non Volatile Mass Measurements*

The EI mass data from the two way inter comparison is presented below in Figure 50. As discussed earlier both reference systems had both an LII and MSS. It is observed that again as engine power decreases so too does the measured EI mass for both the Swiss and EU/EASA reference systems.

It is noted that typically the EU/EASA reference system measures higher mass than the comparative Swiss measurement on both of its mass analysers, with both MSS analysers measuring higher than their comparative LII instruments. It should however be noted that if only looking at primary mass instruments namely; the LII on the EU/EASA system and the MSS on the Swiss system then the data seems to offer very good agreement with the error bars often over-lapping. As discussed earlier the Swiss secondary analyser is plumbed using an additional 3m heated line which may offer some explanation for the unit reading the lowest out of the four analysers.

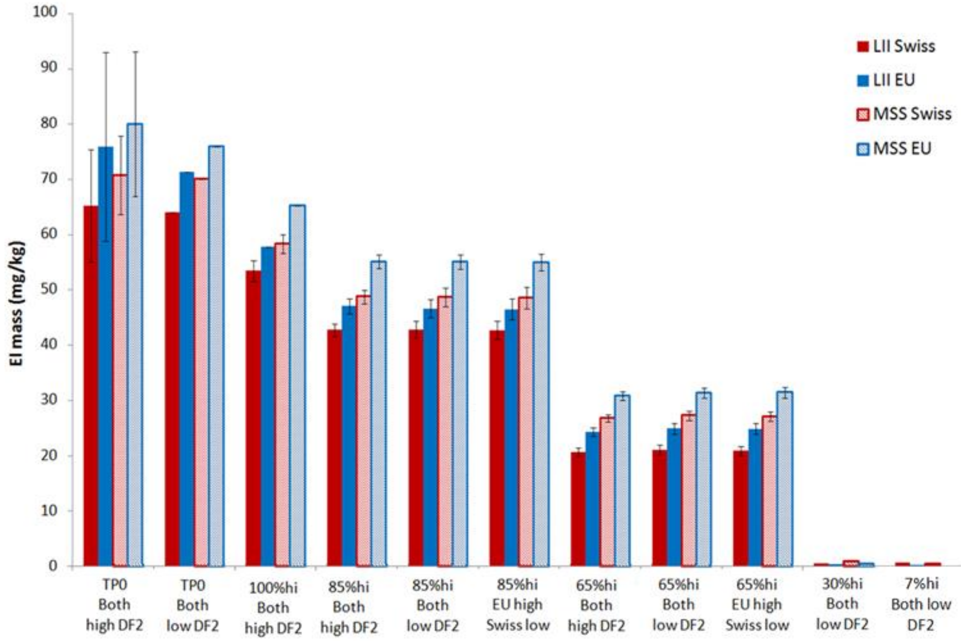


Figure 50 Two way inter-comparison EI Mass measurements from CFM567B26/3, using multi probe, 24th August 2013. High DF2 equates to 169 (250 PCRF), low DF2 equates to 63 (100 PCRF)

Again the two reference systems are compared by normalising their data to each other. Figure 51 shows the normalised data for the Swiss and EU/EASA systems for the LII data. It can be seen that typically the Swiss LII reads 14% lower than the comparable EU/EASA unit.

Again most of the data points lie within the 20% band which was also calculated for mass measurement in earlier studies (SAMPLE III SC02). It should be noted that mass data close to or below the LOD, lie on or close to the y-axis. This is due to the consequence of the data being noisy (see section 7.3.9) and thus the ratio of this data produces very large differences. To keep the axes scale of this type of graph consistent throughout the document, not all of this noisy data (which is not traceable) is shown on these graphs.

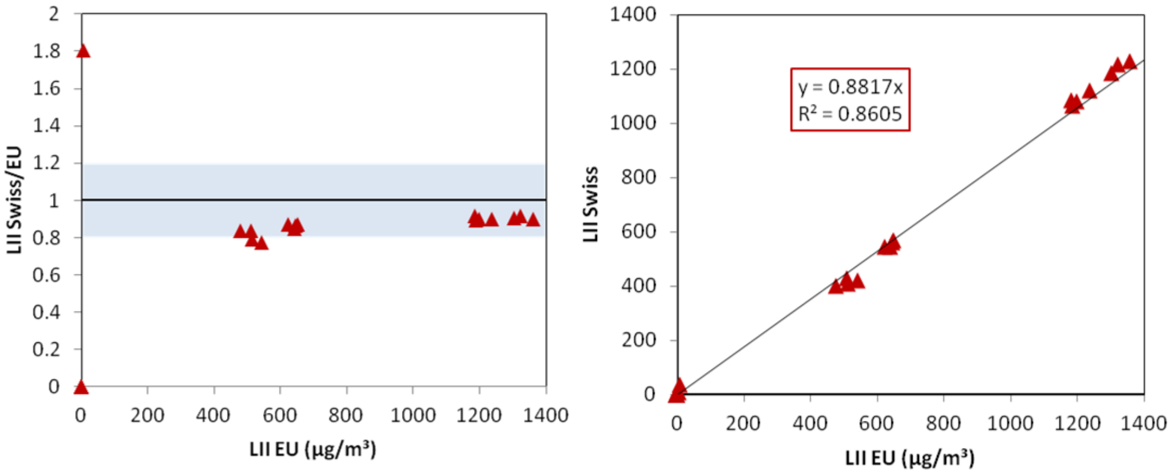


Figure 51 Two Way inter-comparison LII measurements from CFM567B26/3, using multipoint probe, 24th August 2013

Similar normalised data is presented below in Figure 52 for the MSS units; again the Swiss reference system reads typically 11% lower than the comparable EU/EASA system, but again the majority of the data points lay within expected 20% uncertainty bands.

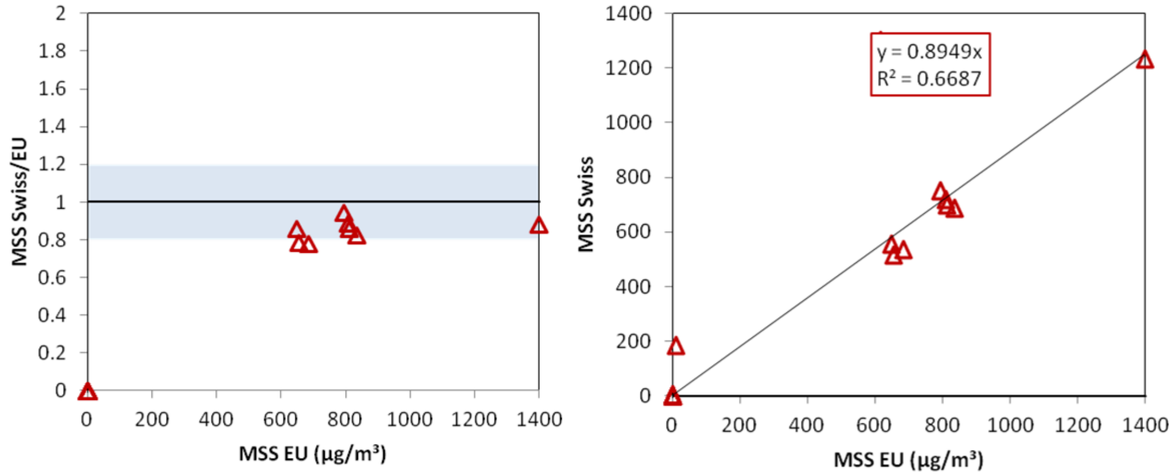


Figure 52 Two Way inter-comparison MSS measurements from CFM567B26/3, using multipoint probe, 24th August 2013

7.3.4 Three Way Swiss Fixed, North American Mobile & EU/EASA Mobile Reference System inter-comparison

The three way inter-comparison between the Swiss Fixed, North American and EU/EASA mobile reference systems was completed as detailed in Table 24, over a three day period on the 3rd, 4th & 5th of August 2013. On the 3rd of August 2013 a 10 point engine down curve was conducted in order to gain a detailed inter comparison across the full engine power range. The 4th August 2013 was utilised to conduct a further 4 repeats on a 5 point subset of the power curve (including the LTO cycle) which was necessary to determine day to day uncertainty witnessed in comparative reference systems. Finally an additional 5 point curve was conducted on the 5th August 2013 to give further day to day uncertainty data, whilst there was also a mass instrument line dependency test conducted by the North American and Swiss teams which involved operating the North American MSS mass instrument on the Empa sampling line.

7.3.4.1 *Non Volatile Number Measurements*

Non volatile PM number concentrations for the three systems running in parallel given for a 10 point engine down curve conducted on the 3rd August 2013 are presented in Figure 53. It is noted that the nvPM number trends witnessed by all three systems are similar with the maximum loadings per fuel burn being witnessed at 85% power, followed by 100% then reducing concentrations with reducing power loads. It is noted that the reducing trend of concentration from 85% to 65% is remarkably more noticeable than observed in the two way inter-comparison where there was no difference observed between these power conditions. However, it should be recognised that the ambient temperature was considerably higher during the 3 way testing which could contribute to this observation, as the engine inlet conditions for the same engine condition (same T3) will be different between the two ambient temperatures and this comparison does not use actual measured proprietary engine data, thus engine conditions with the same title are not directly comparable between the 2 way and 3 way testing.

It is again noted that the Swiss fixed reference system measures significantly higher than the comparative EU/EASA mobile reference system, with the North American reference system quoting values comparable to those of the EU/EASA system with standard deviations around the respective averages often over lapping. This agreement is in contradiction to the pre-testing laboratory inter-comparison of the AVL APC's in isolation, which displayed much better agreement of the Swiss and North American units with the EU/EASA system consistently measuring lower.

Closer interrogation of the CPC data below the traceable measurement range showed that the EU/EASA system measured slightly lower than the North American system. This may support the findings of the pre-test laboratory inter-comparison that observed the EU/EASA number counting system counting comparatively lower at smaller size distributions, which are typically observed at lower powers.

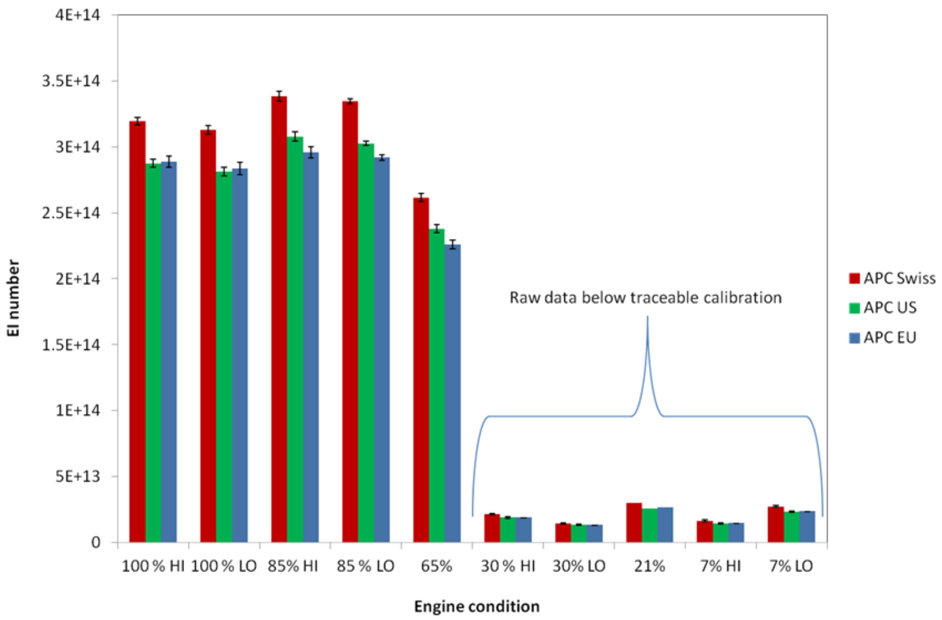


Figure 53 Three Way inter-comparison EI Number measurements from CFM567B26/3, using single probe, 3rd August 2013

It is worth noting that even using the lowest PCRF of 100, with the primary diluter dilution factor operating in the range of 8-13 specified in AIR 6241, that for the two lower power conditions specified in the LTO the number counter was measuring raw counts lower than its traceable calibration (also observed in the North American and Swiss systems). However, though the authors are confident in the trends at these lower raw counts; it should be noted that the uncertainty at these points could be greater than the 10% linearity allowance (as per AIR6241) in the traceably calibrated range.

Again to assess the actual variation between comparative reference systems the test point data taken by the other reference systems is normalised against the values determined by the EU/EASA system, with the data presented in Figure 54 (a&b). For this test series both the Swiss and North American systems agreed within the theoretically calculated expected uncertainty of ±20%. The normalised data shows that in this test configuration the Swiss system typically measured approximately 12% higher than the EU/EASA system with an R^2

of 0.9992, the North American system however displayed very good agreement measuring typically within 2% of the EU/EASA system with an R^2 value of 0.9989.

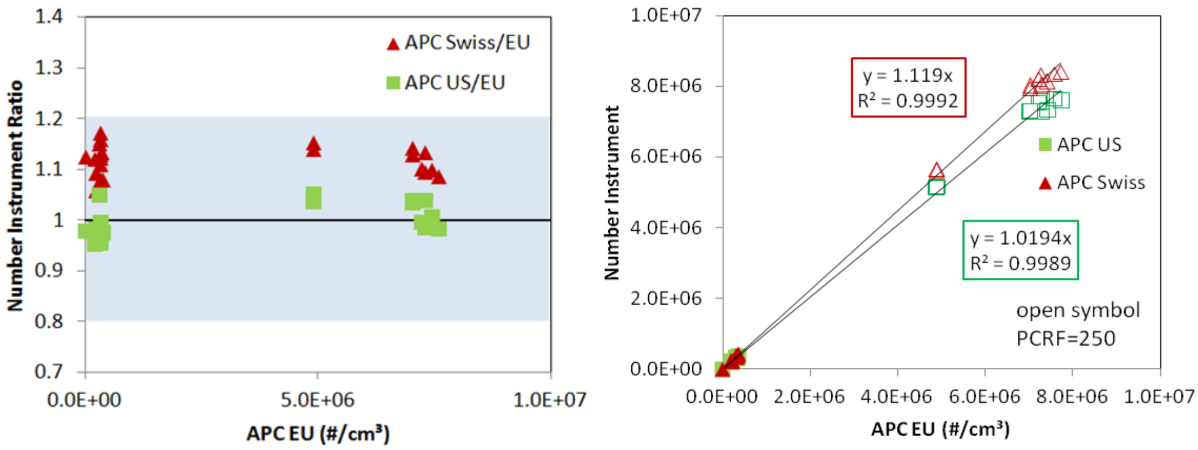


Figure 54 (a&b) Three Way inter-comparison AVL APC (nvPMnum) measurements from CFM567B26/3, using single probe, 3rd August 2013

Again EI nvPM number data is presented for the three reference systems for various power conditions for the 4th August 2013. As discussed earlier 4 repeats of a 5 point power curve were conducted with average values and standard deviations given for the 3 systems in Figure 55. Again it is observed that the Swiss system reports values slightly greater than those witnessed by the North American and EU/EASA systems which again display statistically identical values. As seen in the 2 way inter-comparison the cruise type (65%) power condition displays similar PM number values to those of take-off like conditions.

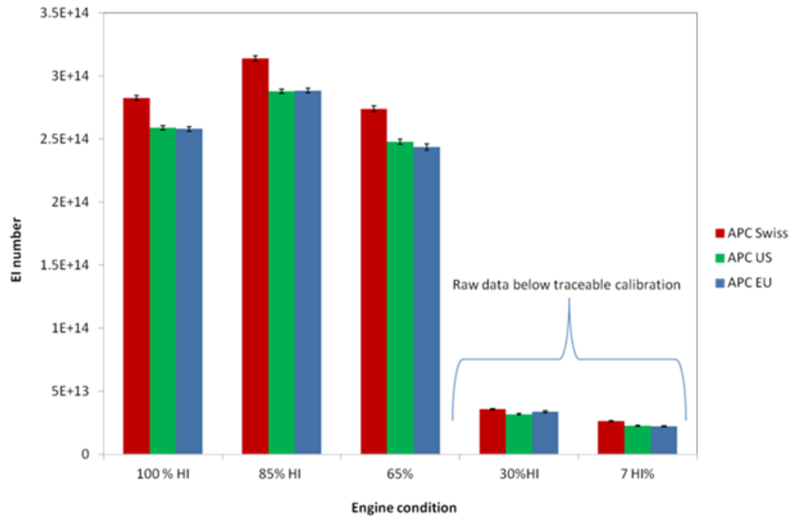


Figure 55 Three Way inter-comparison EI Number measurements from CFM567B26/3, using single probe, 4th August 2013

The Swiss and North American reference systems are normalised against the EU/EASA system with the majority of measured data points lying within the suggested 20% uncertainty bands. Again it is noted that the Swiss system witnessed nvPM number values typically 12% higher than the North American and EU/EASA systems with a coefficient of determination of 0.9982. The North American reference values were again closely matched with the EU/EASA system reading on average 0.5% higher with a coefficient of determination of 0.9989.

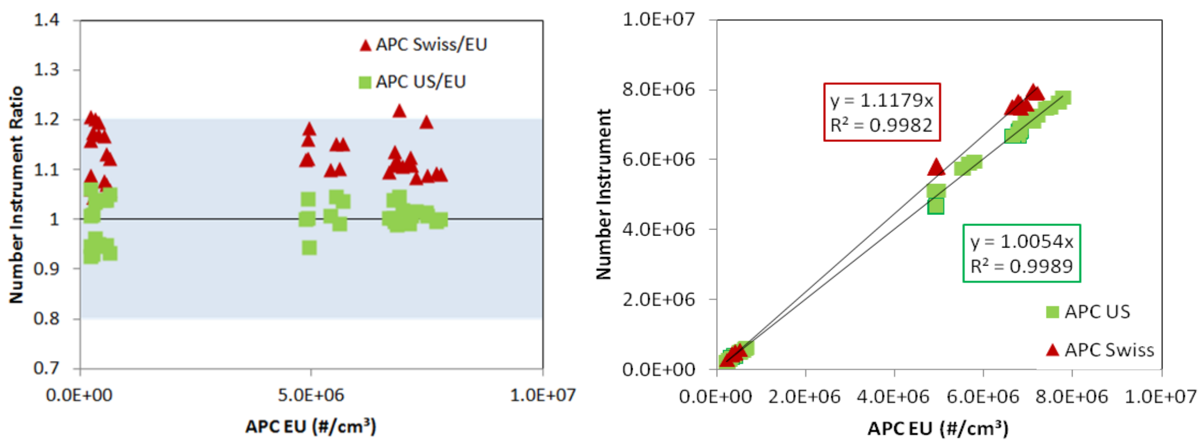


Figure 56 Three Way inter-comparison AVL APC (nvPMnum) measurements from CFM567B26/3, using single probe, 4th August 2013

The data from the last day of three way testing performed on the 5th August 2013 is presented in Figure 57. Again a 5 point power curve was conducted and again the trend of highest EI number was observed on all three systems for the 85% power condition followed by 100% and 65% before considerably lower conditions for the 30% & 7% thrust conditions.

As witnessed through all the comparisons again the Swiss unit measured higher than the North American and EU/EASA systems with again excellent agreement between the North American and EU/EASA systems.

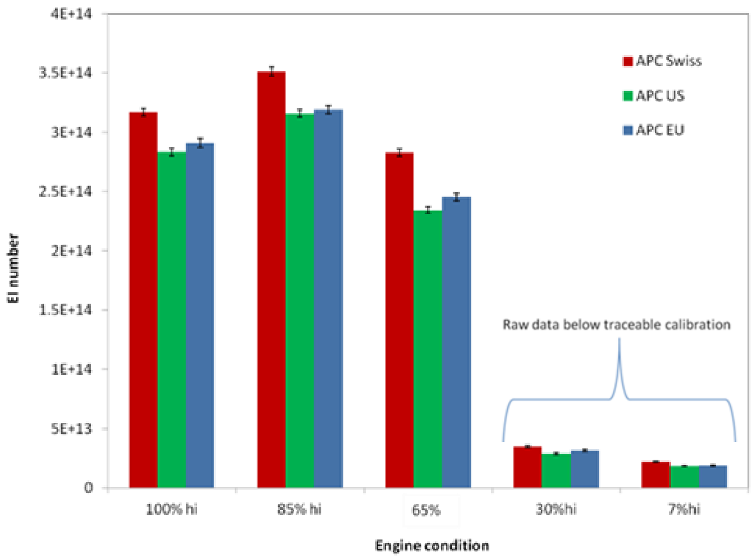


Figure 57 Three Way inter-comparison EI Number measurements from CFM567B26/3, using single probe, 5th August 2013

Again normalised data sets are presented in Figure 58 with the majority of data again lying within the expected 20% uncertainty band. The Swiss system measures 11-12% higher than the North American and EU/EASA systems with a high coefficient off determination of 0.9985. However, in contradiction to data obtained on the 3rd and 4th August, the EU/EASA system measures higher than the North American system across the power spectrum. The North American system shows agreement of approximately 2% with a coefficient of determination of 0.9996.

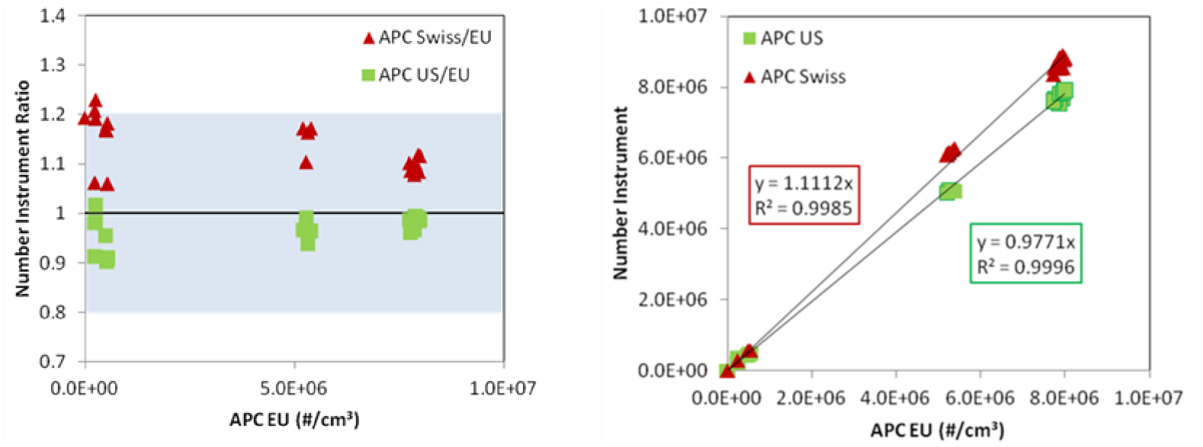


Figure 58 Three Way inter-comparison AVL APC (nvPMnum) measurements from CFM567B26/3, using single probe, 5th August 2013

7.3.4.2 *Non Volatile Mass Measurements*

EI mass data for the three way comparison conducted on the 3rd August 2013 is presented in Figure 59, it is observed that there is good agreement between the EU/EASA and Swiss mass analysers with the MSS giving values higher than the comparable LII analyser. It is noted that the North American MSS reads considerably lower than the other two MSS analysers during this inter-comparison and is seen to have high levels of noise denoted by the large standard deviation bars, this as discussed earlier was attributed to pressure fluctuations caused by the diaphragm pump used to pump the sample through the splitter oven, and was remedied for later experiments by adding a dead volume between the pump and the MSS measurement cell.

It is also observed that for all power conditions less than 65% all of the analysers were below their 3 x limit of detection of 10µg/m^3.

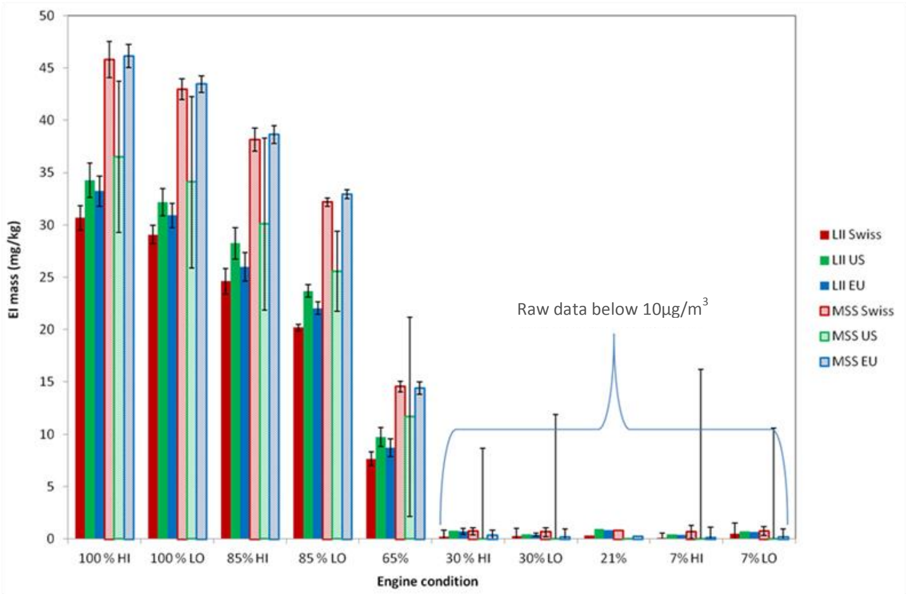


Figure 59 Three Way inter-comparison EI Mass measurements from CFM567B26/3, using single probe, 3rd August 2013

The LII and MSS data for both the North American and Swiss systems are normalised against the EU/EASA system and presented in Figure 60 & Figure 61 respectively. As can be seen for the LII data again the majority of readings between the Swiss and North American systems lie within the expected 20% uncertainty band with the North American system typically reading approximately 5% higher than the EU/EASA system and the Swiss system measuring 8% lower with good coefficients of determination of greater than 0.999.

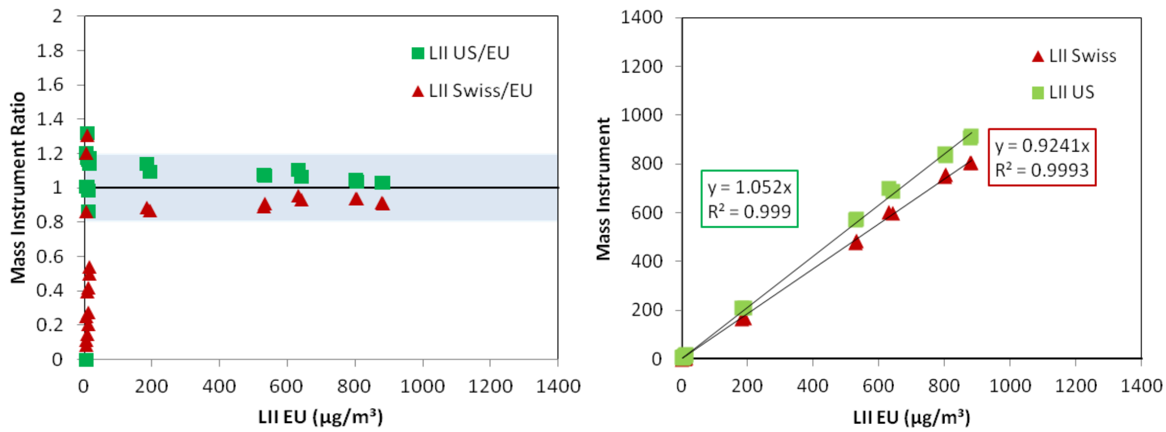


Figure 60 Three Way inter-comparison LII measurements from CFM567B26/3, using single probe, 3rd August 2013

As noted in Figure 59 there was more variation in the measured MSS values for this inter-comparison with regard to the North American reference system, which typically measured 21.5% lower than the other two Swiss and EU/EASA MSS units which offered excellent agreement of within 2%. The coefficients of determination are high for the Swiss EU/EASA comparison with an agreement of 0.9996.

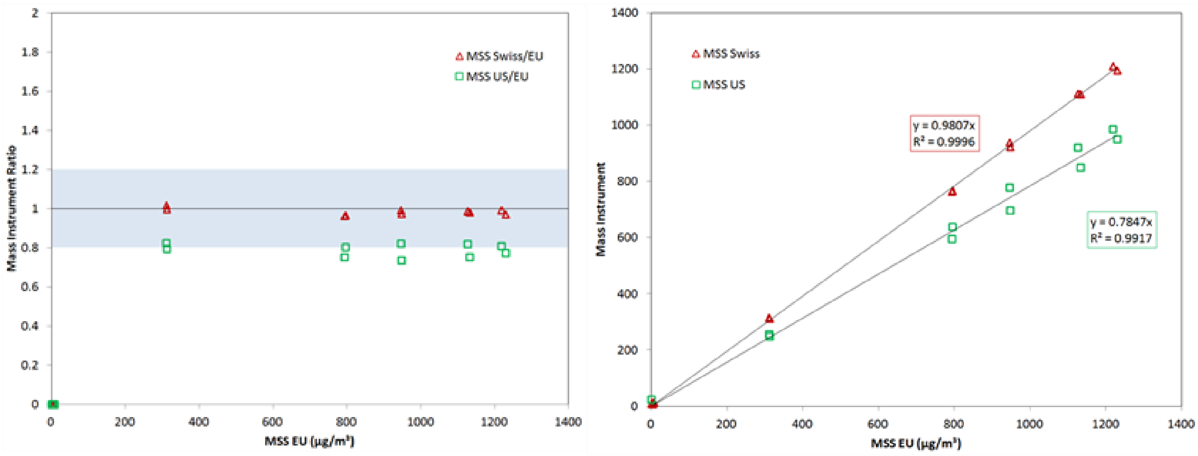


Figure 61 Three Way inter-comparison MSS measurements from CFM567B26/3, using single probe, 3rd August 2013

The EU/EASA MSS is normalised against the EU/EASA LII and presented in Figure 62. For this data set it is observed that if the two types of analyser are compared to each other that they do not agree within the expected 20% band, with a typical offset of 43%. On inspection of Figure 62 it can be seen that the relative offset of the two analysers is not constant, with agreement getting closer at higher mass loadings. Higher mass loadings occur at higher powers but the engine exhaust particle signature also changes making it impossible to determine the sensitivity of the trend with changing engine power. The particle signature changes include: morphology, volatile loading, size distribution etc. All that can be stated is that at higher powers, where the agreement is better, the engine exhaust has typically larger size distributions with a lower volatile fraction. However, it is not possible to state whether either of these phenomena are responsible for the reduction in offset.

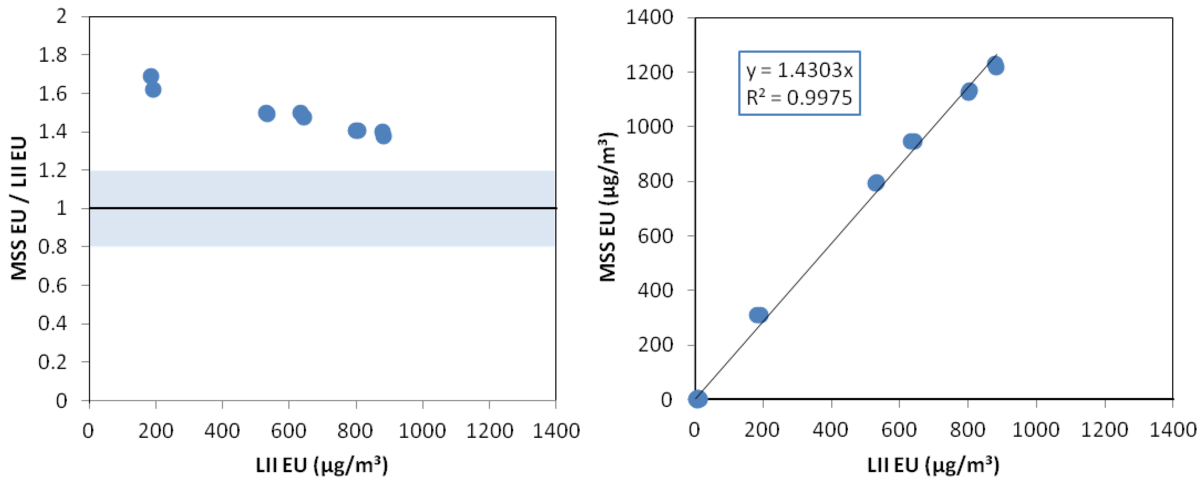


Figure 62 EU/EASA reference system Mass instrument comparison measurements from CFM567B26/3, using single probe, 3rd August 2013

In order to try and assess a level of variation in all of the mass analysers during this data set, each of the six mass analysers (both types on each of the reference systems) was normalised against the average of the six, with the data presented graphically in Figure 63.

As this graph is only to demonstrate the scatter in mass measurement, the identity of each individual mass instrument is not given in Figure 63, with MSS instruments highlighted as blue diamonds and LII as red circles. As can be seen if the data is presented this way then the majority of analysers lie within or close to the 20% expected boundary, however, as it is not possible to ascertain the true non-volatile mass value it is unknown whether the average about which this scatter is based is representative of the 'true' answer, and thus whether the analysers are within the expected 20% measurement uncertainty.

As such it would be expected that the variation should be smaller when comparing to an average derived using specific instrument type results. However, to assess the AIR6241 methodology, considering both types of analyser for a specific engine power condition, the total variation in mass concentration could be up to 60% (+30% to -30%), which is larger than expectations within SAE E31.

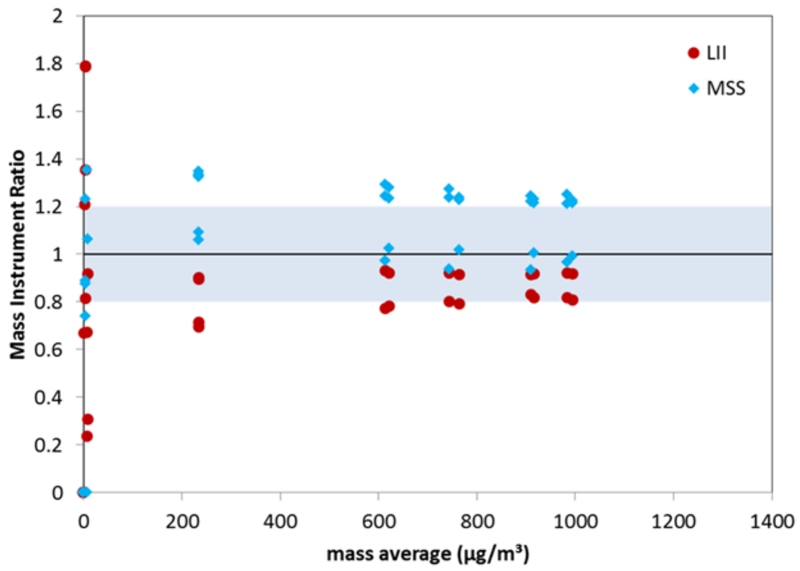


Figure 63 Three Way inter-comparison total nvPM mass measurements from CFM567B26/3, using single probe, 3rd August 2013

A similar three way experiment as discussed above for the 3rd August 2013 was conducted on the 4th August 2013, with a higher repetition of a smaller number of power conditions investigated including the four LTO conditions plus a cruise like 65% power. A summary of all of the mass instruments is given below in Figure 64, it is firstly noted that the noise witnessed on the North American MSS unit on the 3rd August 2013 was vastly reduced by the addition of a 'dampening volume' between the diaphragm pump and MSS as discussed earlier.

Excellent agreement between the Swiss and EU/EASA reference system mass analysers is seen with the North American reading slightly lower values with both the LII and MSS, which is in contradiction with the LII values observed the previous day which showed higher values on the North American system.

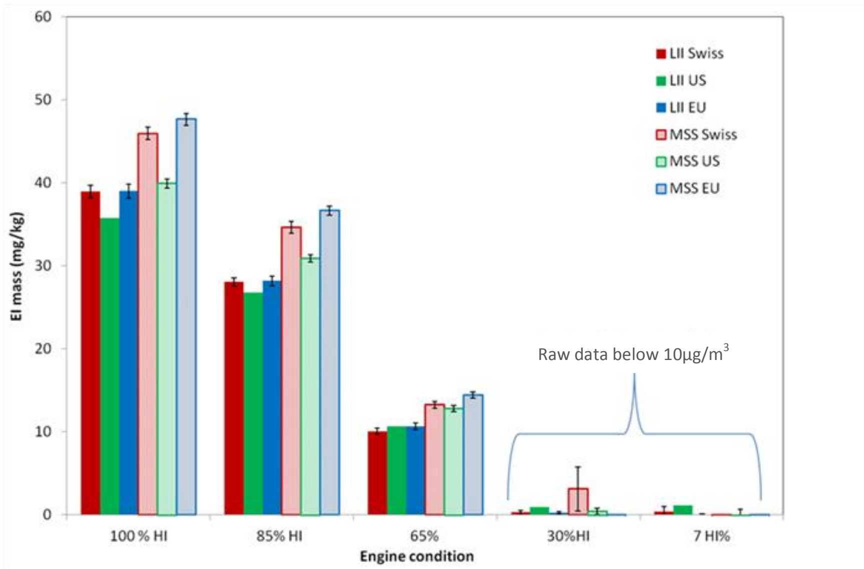
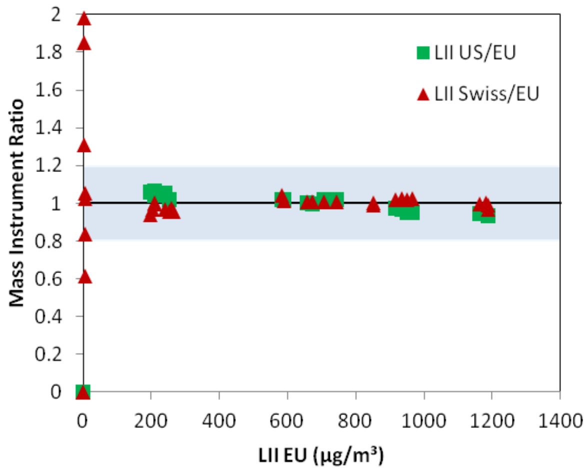


Figure 64 Three Way inter-comparison Average EI Mass measurements from CFM567B26/3, using single probe, 4th August 2013

Both the Swiss and North American reference LII and MSS units are normalised against their comparative EU/EASA analyser with the data presented in Figure 65 & Figure 66 respectively.

As observed earlier, excellent agreement is witnessed for all of the analysers if compared with analysers of their own type, with average offsets from the EU/EASA analyser of 0.5% and 3% witnessed for the Swiss and North American LII units respectively. It can be seen in Figure 64 that the North American EI offset reduces as the engine is reduced in power, with a maximum offset of approximately 10% at high powers.



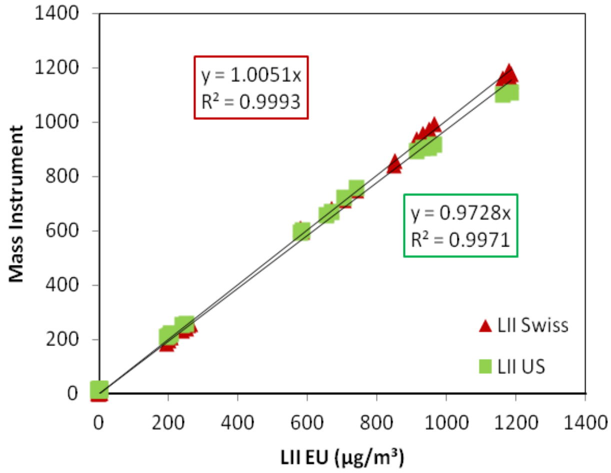


Figure 65 Three Way inter-comparison LII measurements from CFM567B26/3, using single probe, 4th August 2013

All MSS comparisons are also within the 20% error band with a typical 4% offset witnessed on the Swiss system and a 16% offset with the North American reference. It is noted that the coefficient of determination for the Swiss MSS normalisation is lower than typically witnessed at 0.975, and this seems to be forced by a scatter of data at high power (mass loading) conditions. On examination of Figure 64, it is observed that the standard deviation at this point on the Swiss and EU/EASA systems are no larger than at other powers, which suggests that this spread may in some part be attributed to subtle changes in engine power (and therefore diluted CO_2), between repeat points which the EI calculation helps to address.

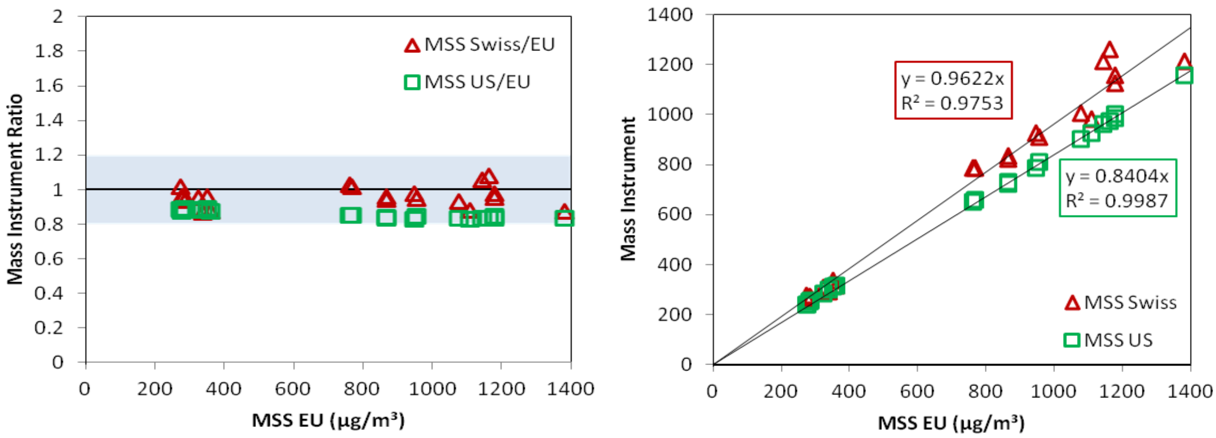


Figure 66 Three Way inter-comparison MSS measurements from CFM567B26/3, using single probe, 4th August 2013

A summary plot showing all mass data normalised against an average mass loading, (as discussed earlier for the 3rd August 2013) taken by all six analysers is given for the 4th August 2013. It is again observed that the majority of the test points lie within the expected 20% band, with the same caveat regarding the representativeness of the average value to that of the 'true' nvPM value.

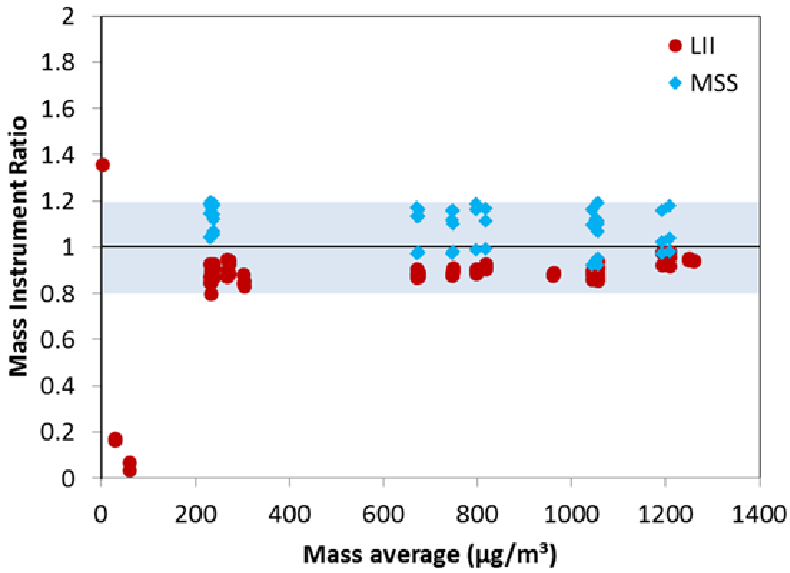


Figure 67 Three Way inter-comparison total nvPM mass measurements from CFM567B26/3, using single probe, 4th August 2013

As mentioned earlier, another 5 point engine power, three way inter-comparison was conducted on the 5th August 2013 on the leased engine, again a summary of all of the mass analysers is given by Figure 68. As discussed earlier, for this test the North American reference MSS was positioned on the Swiss dump line together with the Swiss LII and it is immediately observed that the unit which had consistently been measuring considerably lower than its counterparts on previous days was although still reading lower, was now more comparable to the other MSS units. Again it was noted that there was good agreement between the comparable mass analyser types across all reference systems with the MSS units typically reading higher than their comparative LII counterparts.

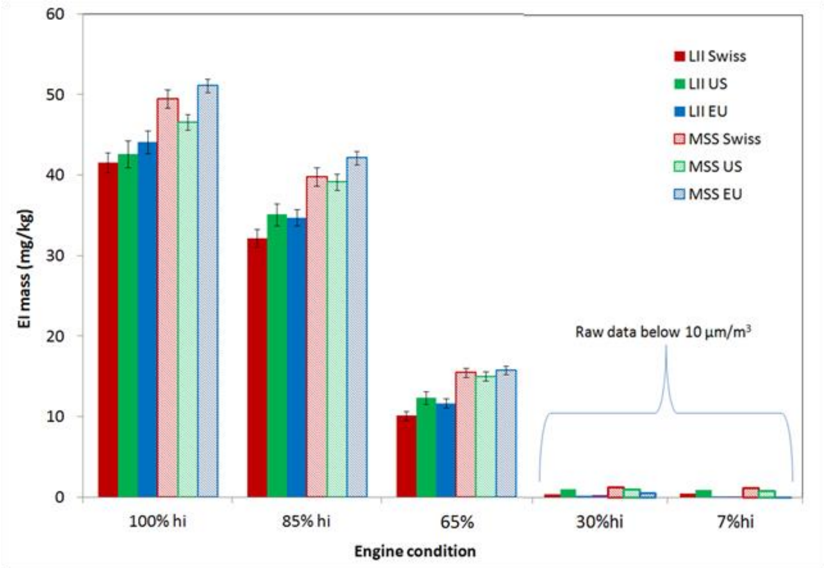


Figure 68 Three Way inter-comparison Average EI Mass measurements from CFM567B26/3, using single probe, 5th August 2013

Both the Swiss and North American LII and MSS are again normalised to the EU/EASA system and the data presented in Figure 69 & Figure 70. It is seen that on the 5th August 2013 that all 3 LII and all 3 MSS agreed typically within approximately 2-8%, which is a lower variation than on both earlier 3 way tests.

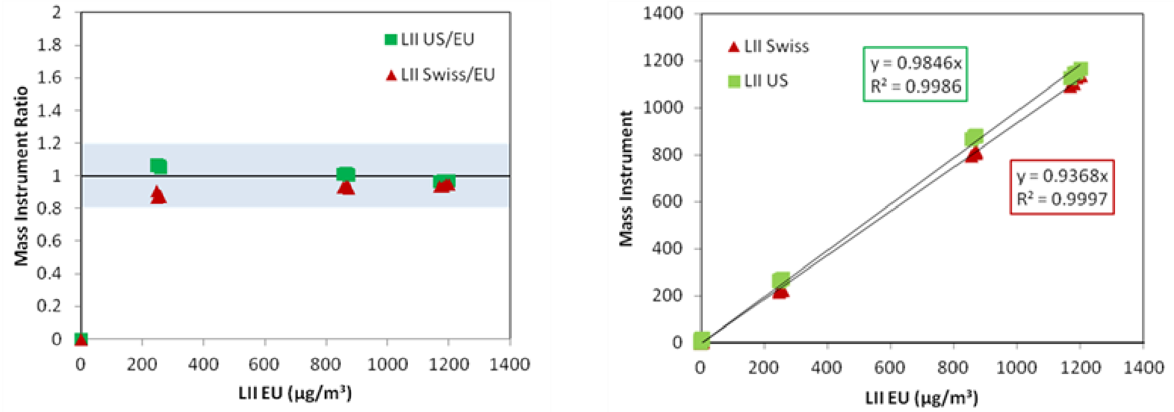


Figure 69 Three Way inter-comparison LII measurements from CFM567B26/3, using single probe, 5th August 2013

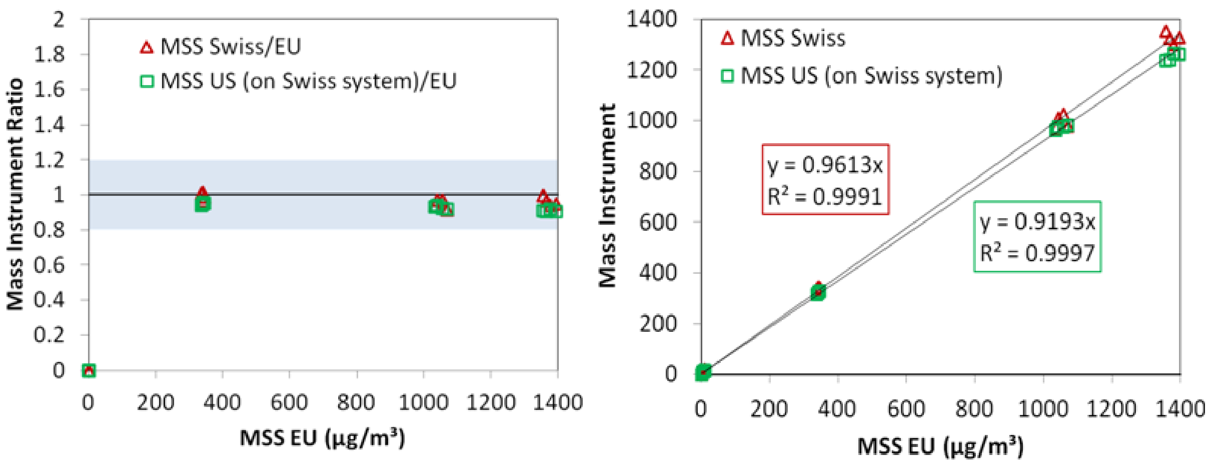


Figure 70 Three Way inter-comparison MSS measurements from CFM567B26/3, using single probe, 5th August 2013

A summary graph of all the mass analysers normalised against their average reading is presented for the 5th August 2013 in Figure 71, with again the majority of analyser data points lying in or around the 20% variation band. It is again highlighted that this variation is against an average of all analysers, which may not be representative of the 'true' mass measurement. Therefore this graph can also be interpreted to show variation between two distinct analysers of different type; at a given engine condition could be considerably higher than this (up to 40-50%).

It is again witnessed, as was shown in the earlier intercomparison testing, that it appears that there is better agreement between the different measurement methodologies at higher power/ mass loadings and this appears to be observed on each of the three reference systems, however again the authors cannot give conclusive evidence as to why this should be the case. The large spread of mass data very close to the y-axis is due to the effect of normalising data that is close to or below the LOD of the instrument.

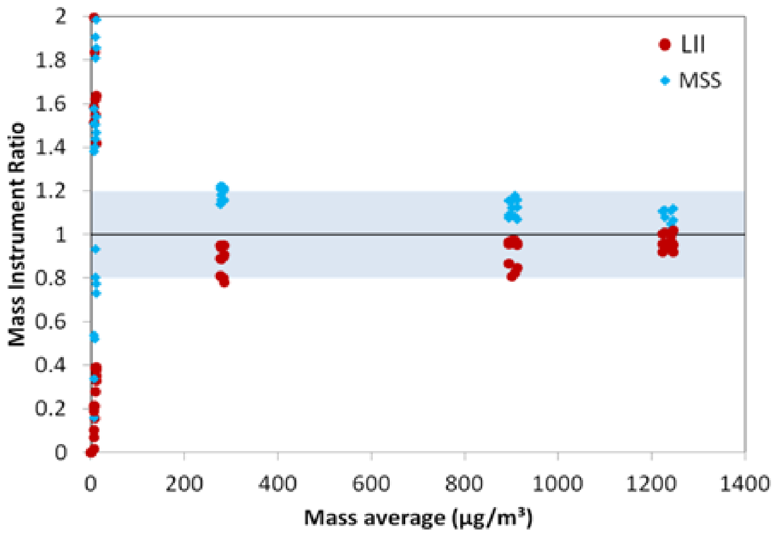


Figure 71 Three Way inter-comparison total nvPM mass measurements from CFM567B26/3, using single probe, 5th August 2013

7.3.4.3 *PM Size Distribution Measurements*

During the three way inter-comparison testing both the EU/EASA mobile reference system and the North American mobile reference system utilised Cambustion DMS-500 size analysers with matched unheated sampling lines to sample from the cyclone and secondary splitter oven (5PTS).

Data from one representative engine power curve conducted on the 4th August 2013 for both the EU/EASA and North American systems is presented graphically and numerically below in Figure 72 & Table 26 respectively.

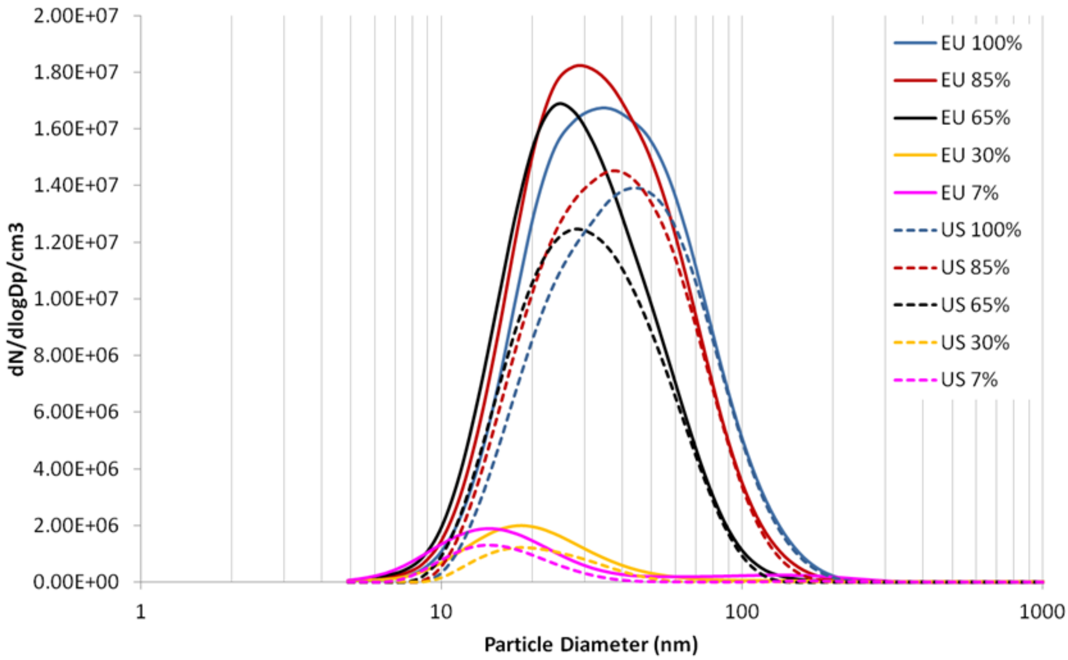


Figure 72 PM size distribution (dilution corrected) from EU/EASA & North American Mobile reference systems performed during three way inter-comparison, 4th August 2013. Distributions are averaged over a 30s period.

As can be seen in agreement with previous studies using engines from the CFM family, as the power of the engine increases, both the PM size distribution mean diameter and number count increase up to 85% power. This trend is observed on both systems, with total number counts typically ~20% higher on the EU/EASA reference system for high engine conditions (larger GMD and lower volatile content) and ~50% higher for the low engine conditions (smaller GMD and higher volatile content). It is noted that the GMD is also generally smaller on the EU/EASA line which may suggest there are more significant losses of smaller particles in the North American system. This type of difference would be indicative of different diffusion losses between the two systems. The vast majority of the North American PM system is more aged (several engine tests) than the EU/EASA system (brand new prior to Zurich testing – but aged for 30 mins as per AIR6241 prior to an engine test), Understanding of long term sampling system penetration drift is an existing PM ARP technical issue. By performing penetration measurements over a long period (multiple engine tests) and/or by inter-comparing systems on a repeated basis will provide a data-set to help resolve this issue. However, the above variations may in part be symptomatic of measurement uncertainty in the two DMS500 units. (Note that both DMS500 units were calibrated by the manufacturer with DMA (traceable via PSL) sized miniCast aerosol two months prior to test campaign).

The difference in total number (as shown in Table 26) is not witnessed on the nvPM number measurement as seen earlier in Section 7.3.4.1. As such this could imply that either:

(i) The penetration efficiency of the EU/EASA VPR at small (15nm to 30nm diameter) particles is lower than shown by the pre-test experiment (section 6.4.1.3). Note the offset observed in the pre-test experiment only accounts for ~5% difference.

(ii) There may be more volatile particles in the EU/EASA reference system line than the North American system which could be due to the lower dilution factor in the primary diluter of the EU/EASA system.

(iii) A combination of these two effects, coupled with the aforementioned unknown instrument measurement uncertainty

Table 26 Numerical (dilution corrected data from DMS-500 for EU/EASA & North American Mobile reference systems performed during three way inter-comparison, 4th August 2013

Target Engine Condition	Total Number #/cm^3		ratio	GMD (nm)		GSD	
	EU/EASA	North American	North American / EU/EASA	EU/EASA	North American	EU/EASA	North American
100%	1.20E+07	9.60E+06	0.80	37.2	40.5	1.81	1.77
85%	1.22E+07	9.71E+06	0.79	33.6	36.4	1.77	1.73
65%	9.99E+06	7.66E+06	0.77	28.5	30.6	1.70	1.67
30%	1.01E+06	5.47E+05	0.54	20.4	20.9	1.71	1.46
7%	1.10E+06	5.40E+05	0.49	20.5	16.1	2.35	1.57

7.3.4.4 *Discussion of Three way inter-comparison testing*

In order to ascertain the inter system variation of the three reference systems, over the three days of testing (3rd, 4th & 5th August 2013) all of the data is normalised against the primary EU/EASA measurement mass analyser namely, the Artium LII-300 and the EU/EASA AVL APC for number, with the results given in Figure 73 (a&b) respectively.

Again a 20% band of uncertainty has been added to the data set, however this band is applying an assumption that the EU/EASA number and mass analysers are quoting the ‘true’ value, which may not a representative assumption which can be adopted to look at total uncertainty of nvPM, but gives a value of how reproducible the other analysers (reference systems) were compared to the EU/EASA system.

As such it can be seen in **Error! Reference source not found.**(a) that there appears to be agreement well within the expected bounds of all the LII analysers with lower variation observed at higher mass loadings.

The reproducibility of the nvPM number measurement between the 3 systems is shown in Figure 73**Error! Reference source not found.** (b). Good agreement is observed with the vast majority of the data within 20%. However, a biased offset with the Swiss system is clearly observed. It has been surmised that the very warm environmental conditions for the Swiss CPC would shift the CPC cut-off

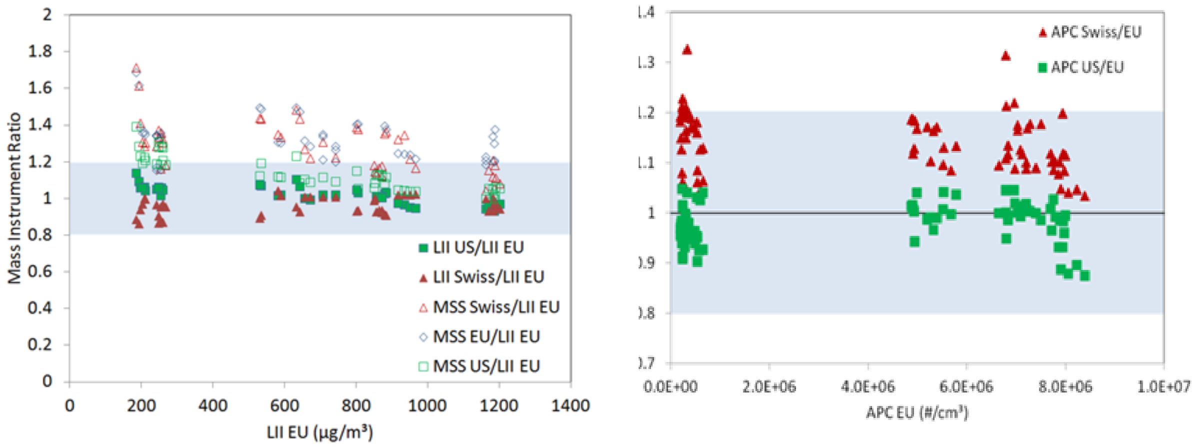


Figure 73 (a&b) AIR 6241 compliant nvPM mass and nvPM number data across all three way experiments from CFM567B26/3, using single probe, 3rd 4th & 5th August 2013

curve to measure smaller particles. However, as shown in SAMPLEII, SAMPLEIII SC01 and SC02, there is very limited evidence to suggest that there are a significant number of non-volatile particles <10nm at the CPC inlet; either generated by aircraft engine combustors or successfully penetrate through the sampling and volatile removal system. Therefore it is unlikely that a CPC cut-off shift to smaller particles is causing the bias. In addition, there are a number of conflicting factors that cause uncertainty on defining a single reason for the bias observed. For example, though the EU/EASA and North American system appear to agree very well it can be seen from the earlier size distribution graphs (Figure 72) that penetrations of the two systems not accounting for measurement uncertainty may be different.

Table 27 below describes possible factors that could cause differences in observed nvPM number concentration.

Table 27 Possible factors effecting observed nvPM number concentration between the 3 systems

Reason	Effect	Reference system status			Effect on observed Number concentration
		EU/EASA	North American	Swiss	
High environmental CPC temperature	Shift CPC cut-point to a smaller size - measure more smaller (<15nm) particles	CPC temperature within instrument limits – similar to North American	CPC temperature within instrument limits – similar to EU/EASA	CPC temperature close to/above instrument limits	**Swiss ↑**
	CPC flow rate different to calibration – STP calculation imprecise				**Swiss ↑**
VPR penetration	Lower penetration – lower CPC number count	Lowest penetration (-5%)	Similar to Swiss	Similar to North American	**EU/EASA ↓**
CPC calibration	Steeper lower cut-point curve – CPC measures fewer smaller (<15nm) particles	Steeper than North American & Swiss	Similar to Swiss	Similar to North American	**EU/EASA ↓**
	Varying linearity curves – CPC measures different particles at low (<2000 #/cm^3) number conc^s	~ -4.7% maximum offset	~ -7% maximum offset	~ -7% maximum offset	**EU/EASA ↑**
Sampling system penetration differences	Lower penetration – lower CPC number count	EU/EASA higher than North American	North American lower than EU/EASA	No direct comparative information during testing	**North American ↓**

Higher random uncertainty is observed for the raw CPC data outside the traceable measurement range (shown by the cluster of dilution corrected APC EU/EASA CPC data located at <2.0E6 p/cm^3 in Figure 73(b). This is likely due to differences in CPC lower cut-point and linearity curves between the systems, which are not traceably calibrated at these low levels with the largest offset from linearity observed for all three CPC's at the lowest calibrated value. Note that if the diluted CO_2 measured concentrations were outside the SAE ARP1256 recommended 20% to 100% analyser FS (which is most likely to occur at the lowest engine conditions) there could be additional uncertainty. However, all the systems were operating in compliance.

It should be stated that the nvPM number measurement in all 3 systems adhered to AIR6241, and despite the above factors for number variability between the systems, good overall agreement was still observed. Improving (where possible) AIR6241 requirements for the above factors will help reduce number measurement variation for the nvPM ARP.

Noting that, as discussed later in section 7.3.8, dilution sensitivity was not observed to be a reason for 3 way comparison data differences on the CFM56-7B/36 engine, on different engine signature dilution sensitivity could be another possible factor if comparative sampling systems are operated at different DF's.

During the 3 way comparison there was discrepancy with the North American MSS, in that when it was measuring on the North American reference system (3rd & 4th August 2013) it reported lower mass loadings than the other two MSS units, however when it was moved across to the Swiss system for the final day of testing (5th August 2013) it started reading comparative mass loadings with the other MSS units.

At this time it is still unknown why this phenomenon was observed and the North American team in conjunction with AVL, the MSS manufacturer, are investigating possible causes. One possible explanation for the originally low readings would be a leak at the inlet to the MSS which would have caused a partial dilution of the PM sample. This leak may then have been remedied on re-connection of the analyser to the North American line. However, this is simply a hypothesis as there is no current evidence to support this theory other than the reduced mass loadings observed on the first two days of comparison. In addition similar MSS inlet pressures were observed between the North American and EU/EASA systems which would indicate that there was not a leak on the North American system.

As can be seen in Figure 73(a) the data set for the MSS units seem comparable to each other as was discussed earlier in the report but as a subset typically measure higher than the comparative LII data for all 3 systems. This data set again highlights the observation that there appears to be better agreement between the two mass analyser technologies at higher mass loadings, which as discussed earlier occurs at higher power conditions when the size distributions are typically larger and the volatile ratio is typically lower, however it should be noted that the morphology of the particles will also have changed in an un-quantified manner.

The non volatile PM number data given in Figure 73(b) also lies typically within the 20% expected boundary, with the North American system typically agreeing with the EU/EASA system within 10%. The Swiss non-volatile number is typically approximately 12% higher than the comparable EU/EASA data. As discussed earlier this would be consistent in trend to that observed in the pre-test (on-site at SR Technics) laboratory test, however could also be symptomatic of a better penetration of particles through the Swiss system compared to the EU/EASA sampling system. However, the latter hypothesis is not supported by the mass data which typically shows higher values on the EU/EASA line.

7.3.5 Undiluted CO_2 comparison

As previously explained, undiluted CO_2 measurements were only taken on the EU/EASA and Swiss systems. The North American DF1 data (for the 3-way comparison) was processed using the EU/EASA undiluted CO_2 measurement, thus it is important to understand if there were any differences in the undiluted CO_2 measurements as it could help explain differences observed in DF1 between all systems. A comparison between the EU/EASA and Swiss undiluted CO_2 measurements (both chilled and semi-dry) for all engine runs during the 3-way and 2-way comparison is shown below in Figure 74.

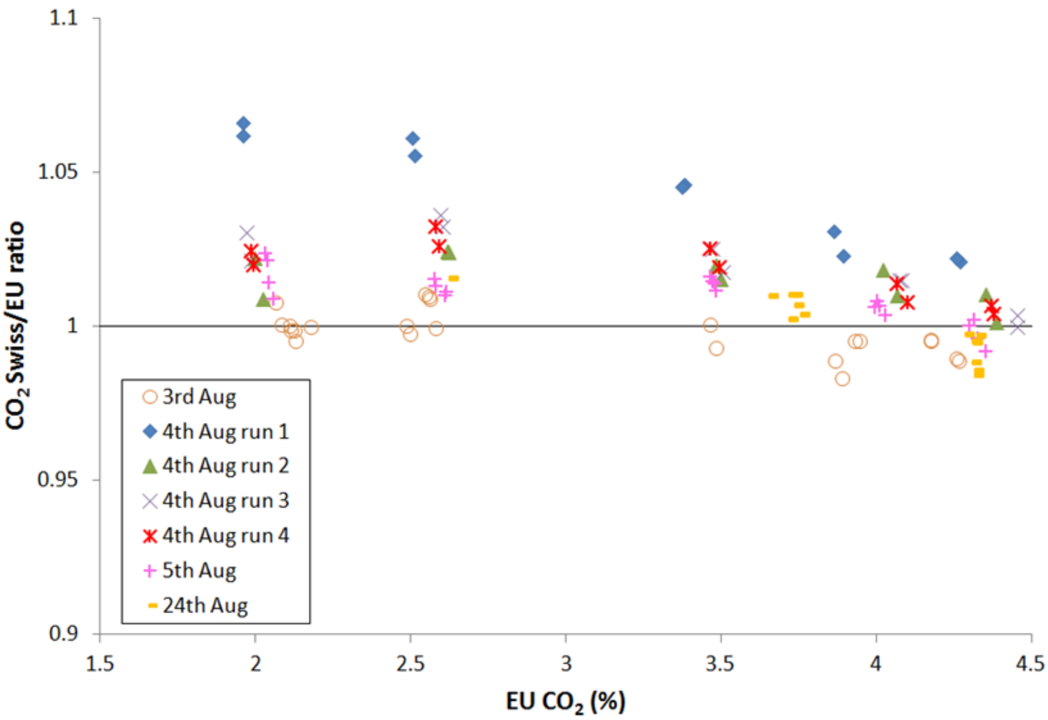


Figure 74 Comparison of undiluted EU/EASA and Swiss CO_2 measurements

It can be observed that the Swiss CO_2 analyser generally reads slightly higher than the EU/EASA CO2 analyser. For all engine runs except for the first run on the 4th August the data is all within 3%. This is within the measurement uncertainty of the ARP1256 performance specifications (noting that different gas calibration span bottles were used for each analyser). It is unknown why there is a larger difference occurring at the start of the 4th August. It is surmised either one or both analysers had not fully warmed up prior to this engine run.

The small positive bias for the Swiss analyser could have a small impact on DF1, causing the Swiss DF1 to read too high or the EU/EASA system to read too low. Either way this finding does not help to explain the DF1 differences observed in Section 7.4.3.

7.3.6 Non Volatile PM Variability

As the dedicated engine was constant through the entire test campaign of SAMPLE III (APRIDE 5) it is possible to investigate the effects of changing ambient conditions and reference system variability by comparing repeat points on different days. Unfortunately due to the varying number of reference systems across the 6 weeks testing, (which required differing sample probe geometries) it is not sensible to compare all repeat points, as probe geometry and position along with flow effects would add to the variability in metrics measured. As such only data from the EU/EASA Mobile reference system operated during the three way inter-comparison, is shown at this time which occurred on the dates of the 3rd, 4th & 5th August 2013 and was measured with the non-representative, single point probe at AIR 6241 compliant flow conditions.

Over the three days testing there were a minimum of 7 repeat points conducted for 5 discreet target power conditions namely 7% (HI), 30% (HI), 65% (HI), 85% (HI) & 100% (HI), EI number and mass data for all these repeat points are presented in Figure 75. Actual measured engine settings and ambient conditions are not taken into account in the graphs below. However, the data is presented here to show what type and magnitude the variability of ambient conditions can have on nvPM and that number and mass are not necessarily varying in the same way.

The ambient effects of this data set have already been discussed in detail in Task 2 (together with use of actual engine measured data), with the data given graphically to determine ambient effect in Figure 6 & Figure 7, thus will not be discussed further at this time. However, it should be noted in the trends of EI mass and EI number in the below figures do not necessarily follow each other. If these trends are ‘real’ then this would indicate that if there are ambient effects they may not be affecting mass and number in the same manner, which maybe implies there is a change in nvPM size distribution, brought about by ambient changes.

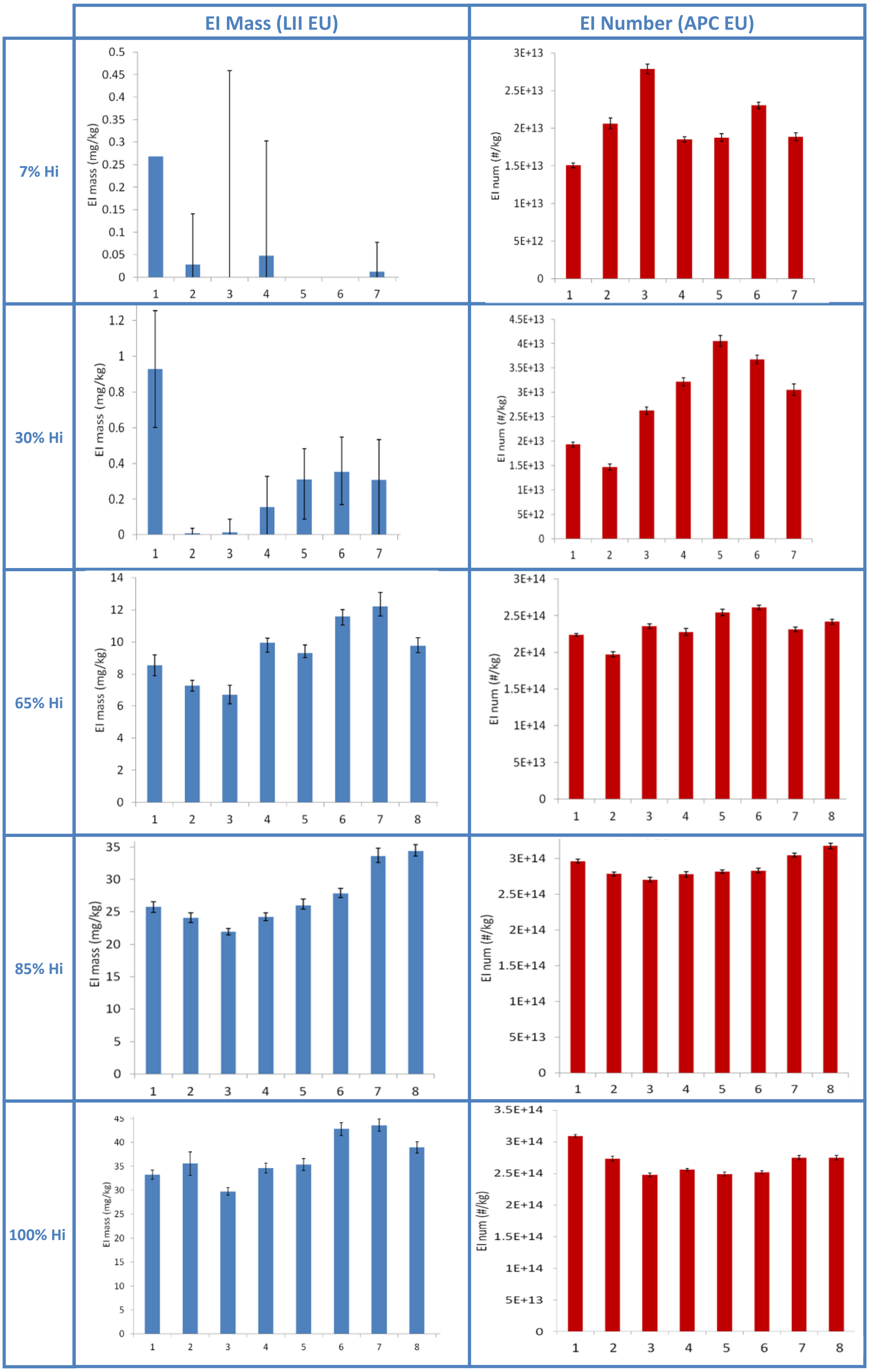


Figure 75 Variability in non volatile PM Mass and Number at various powers for CFM56-7B26/3, single point probe, 3rd, 4th & 5th August 2013

7.3.7 Diluent Composition Sensitivity

As AIR 6241 allows dilution at the primary diluter (3PTS) with either synthetic air or nitrogen it was decided that a sensitivity analysis should be conducted to ensure none of the analysers have sensitivity to the carrier gas composition. As it is known that gas composition can affect the AVL MSS it was necessary to perform a re-zero check when gases were changed. Both the Artium LII and AVL APC are insensitive thus didn't require any calibration before switching gases.

To perform this task during the test matrix on the 3rd August 2013 the EU/EASA diluent gas was switched from zero air to zero nitrogen whilst, the Swiss system remained on zero air (note that the North American system also used zero air during this test, however, the GTS flow rate was not necessarily matched). As such the relative offsets of the nvPM mass & number instruments could be compared between the systems for the two different diluents gases.

Figure 76, Figure 77 & Figure 78 gives a comparison between the measured nvPM number and mass of the EU/EASA and Swiss APC, LII & MSS with the EU/EASA system using nitrogen as a diluent gas.

As can be seen the nvPM number data presented in Figure 76, shows that the Swiss system measures approximately 12.2% higher than the EU/EASA system. This is comparable to the 11.9% offset quoted earlier for the two systems when both using Air as a diluent on the same test day presented in Figure 54, demonstrating the diluents composition has no effect on the measured nvPM number.

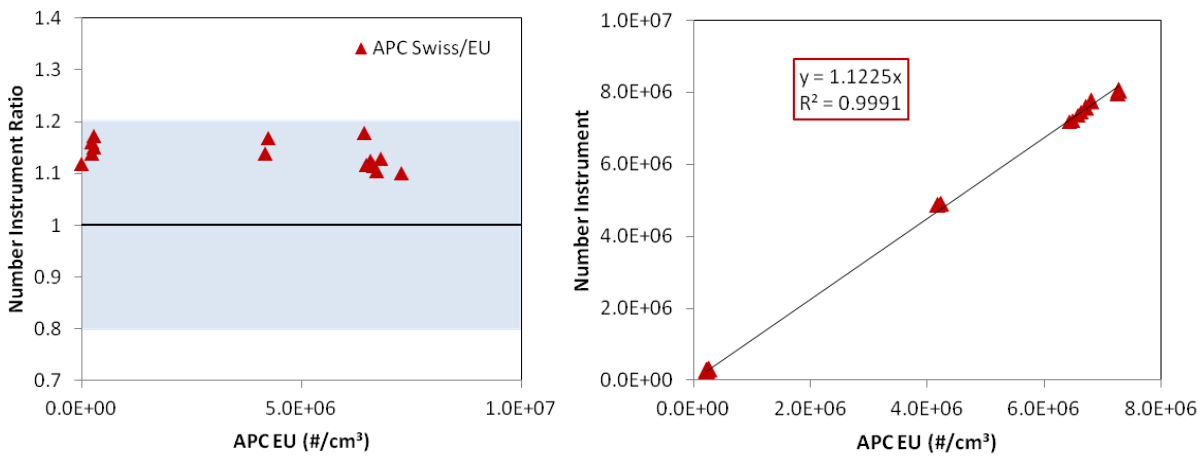


Figure 76 APC Diluent composition sensitivity study conducted during three way inter-comparison testing, 3rd August 2013

In terms of nvPM mass there is still good agreement in the relative offsets, well within what may be expected due to measurement uncertainty however for both the LII and MSS as presented in Figure 77 and Figure 78 there are variations of 12.7% and 4.6% respectively, which are nominally twice as large as those measured on comparable dilution gas of 7.5% and 2% as highlighted in Figure 60 & Figure 61.

As these offsets are well within the expected measurement uncertainty it can be surmised that the diluents switching from air to nitrogen has no discernible impact on nvPM mass measurement, however, it is noted that these observed disparities are typically larger, particularly for the LII instrument compared to other EU/EASA/Swiss inter-comparisons made during the 3 way testing. It is noted that they are very similar in order to those observed during two way testing, so are probably more symptomatic of other measurement uncertainties.

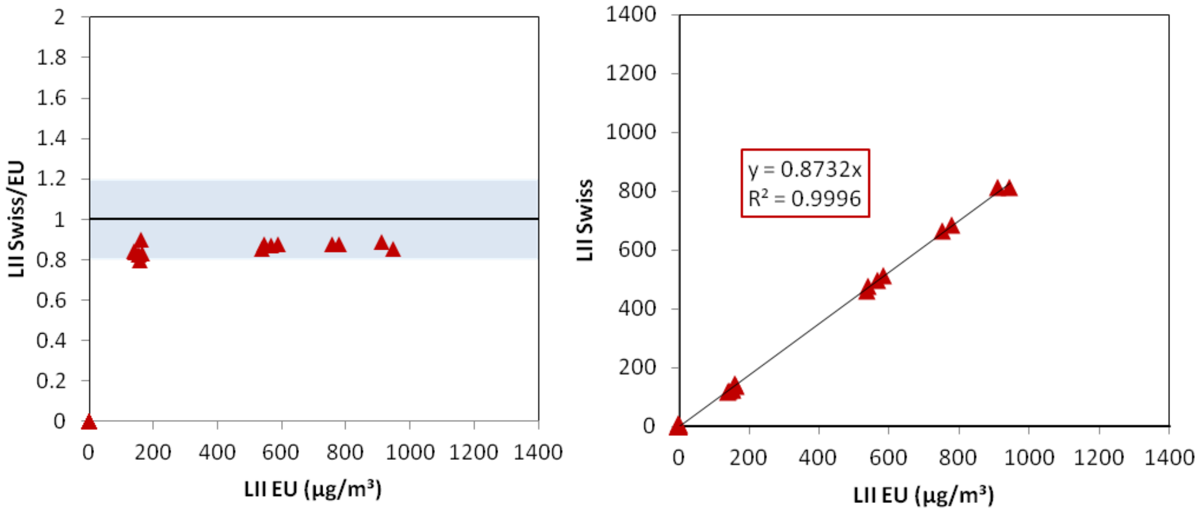


Figure 77 LII Diluent composition sensitivity study conducted during three way inter-comparison testing, 3rd August 2013

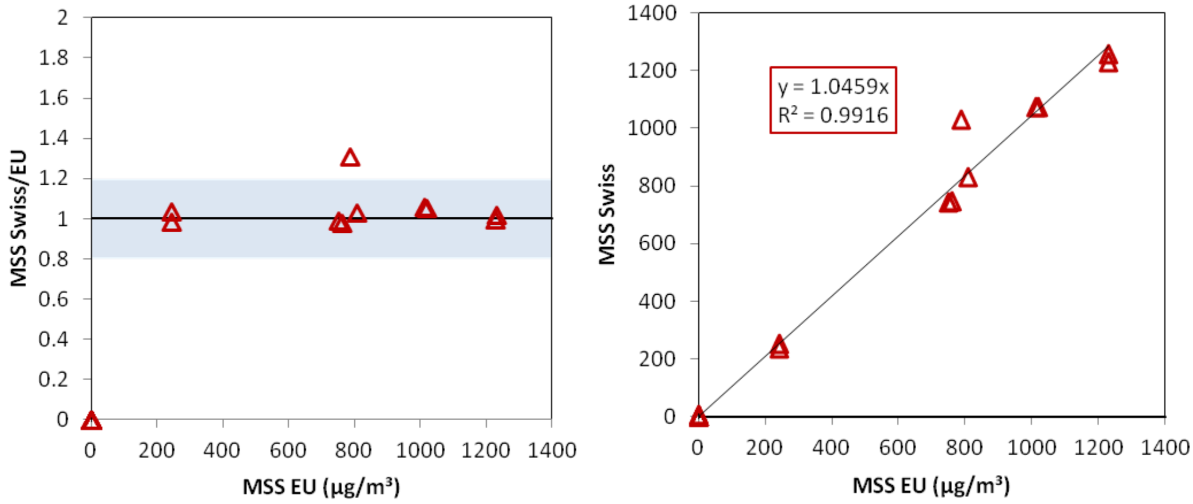


Figure 78 MSS Diluent composition sensitivity study conducted during three way inter-comparison testing, 3rd August 2013

7.3.8 Dilution Factor Sensitivity

Previously during SAMPLE III SC02, it was observed that at high particle loadings, it appeared the primary dilution factor affected the particle concentration measured by the analysers, with higher dilution appearing to provide a better particle penetration, one mechanism proposed to explain this finding was coagulation.

As this original finding was not substantiated by a purpose designed experiment, on the recommendation of the SAE E31, it was decided that a specific experiment investigating the effect of dilution factor on nvPM line penetration be undertaken. Two experiments were conducted on the EU/EASA reference system during SAMPLE III SC03 during the certification-like single system test on the 25th August 2013 and during the 3 way inter comparison conducted on the 4th August 2013.

Figure 79 shows the nvPM number data taken on the 25th August 2013. It can be seen that DF1 was varied on each stable engine condition. Whilst varying DF1 and keeping all other operability parameters in specification of AIR 6241, there appears to be no noticeable trend with regard to increased dilution factor with measured number concentration. It is noted at the Maximum Continuous engine condition that at an increased dilution factor of 14 compared to 11 saw a very marginal increase in measured number. However, for the other engine powers tested namely; 100%, 85% & 65%, the reverse trend of decreased number concentrations with increases in dilution factor.

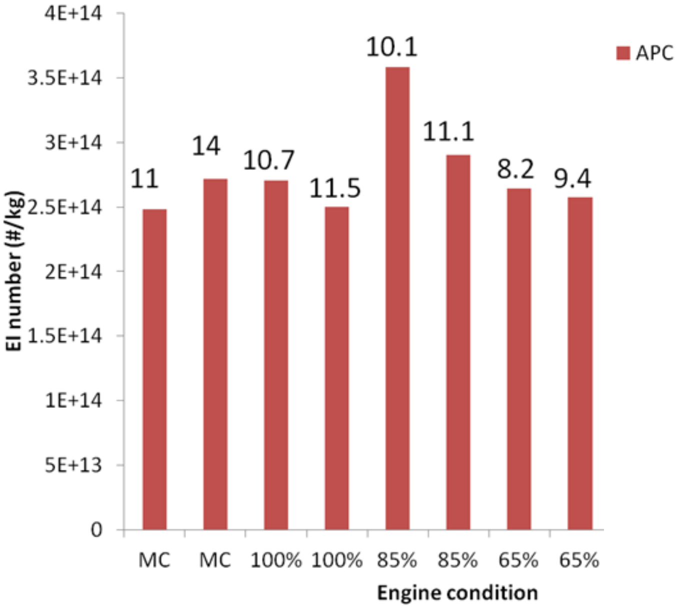


Figure 79 Dilution Factor (DF1) sensitivity for Non Volatile PM number and mass conducted during testing from CFM567B26/3, multipoint probe, 25th August 2013

During this test, a FMPS was also operated investigating PM size distributions, data for the distributions for one power condition (MC) is presented below in Figure 80. As can be seen 3 dilution factors were studied. Two dilution factors, 9 and 14.5, were within AIR 6241 specification and one dilution factor, 6, was an additional non-specification condition. It is noted that for the two compliant dilution factors there is no statistically different result in size distribution or number concentration. However, when comparing to the non-compliant dilution factor of 6 there is a noticeable difference in number concentration with lower number counts.

The size distribution appears nominally identical for the lowest dilution factor case which does not give evidence towards a coagulation affect.

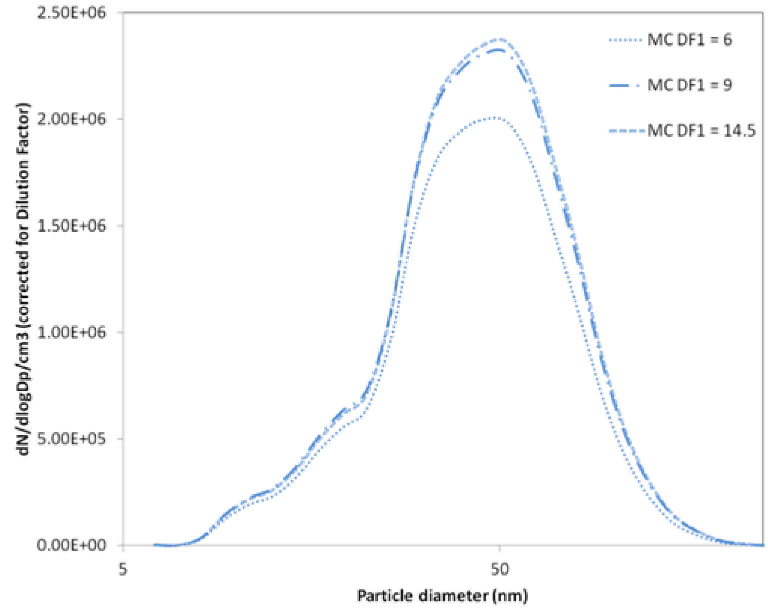


Figure 80 Dilution Factor Sensitivity on PM size distributions measured with TSI FMPS conducted during testing from CFM567B26/3, multipoint probe, 25th August 2013

Data investigating dilution factor sensitivity conducted during the three way testing is presented in Figure 81 for nvPM mass and number for three engine power conditions namely Ground Idle, 65% and 100%.

It can again be observed that there appears to be no statistically significant trends regarding dilution factor and nvPM mass or number across the engine power range.

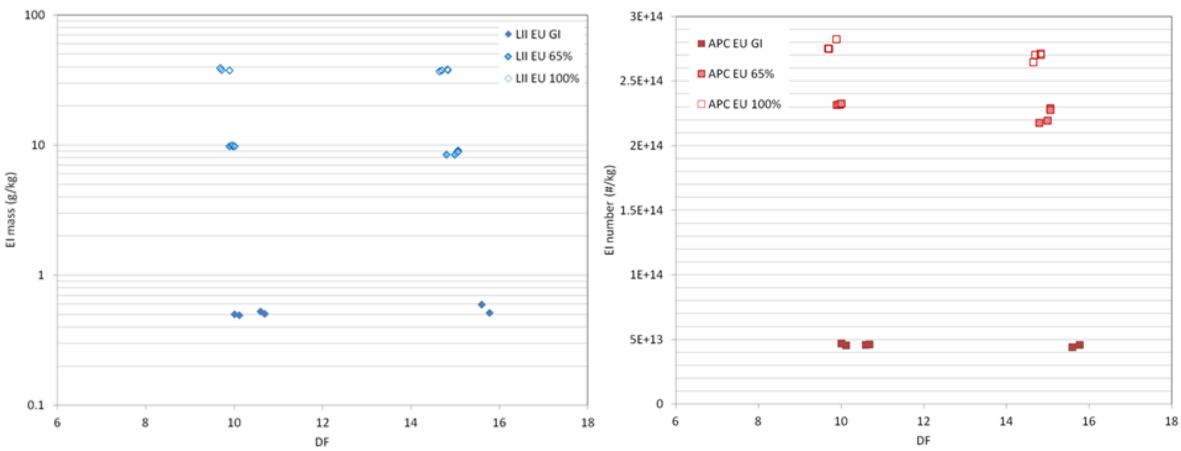


Figure 81 Dilution Factor sensitivity for Non Volatile PM number and mass conducted during testing from CFM567B26/3, multipoint probe, 4th August 2013

It is however, noted that the number concentrations witnessed for this CFM567B26/3 are considerably lower than the concentrations observed during SAMPLE III SC02 using the CFM DAC engine, as such the authors suggest that even though this null finding was found during this test campaign this does not mean that there may not be an affect at higher nvPM number loadings.

7.3.9 Non Volatile PM Stabilisation

It is observed from the engine test timelines in Section 7.3.1 that for some engine test points the nvPM can stabilise fairly quickly (within 1 or 2 mins), however, for some test-points it can take significantly longer (almost 10 mins) to stabilise (though a proportion of this longer time is often due to the engine operator 'over shooting' a specific performance condition test point). Aircraft engines are not designed and built to test for long periods (>10 mins) of time at take-off engine power. In addition, aircraft engine testing is an expensive business (especially for large engines as the higher fuel flow rate dominates the cost) and any additional and cumulative time-on-test will greatly impact the test cost. Thus any reduction in measurement time is beneficial both in engineering and cost terms.

Currently there is no AIR6241 specification for assessing whether the nvPM signature is stable or not. Good engineering practice has been to use human eye visible methods for assessing when the signal appears stable (as was performed during the SAMPLEIII SC03 Zurich engine testing).

Below is a timeline example (for both mass and number) showing stabilisation of the nvPM signal after engine acceleration. The sharp peak 'overshoot' is often observed when accelerating (increasing in engine power). By obtaining nvPM points on a deceleration (decrease in engine power) generally the stabilisation time is shorter so this is recommended practice.

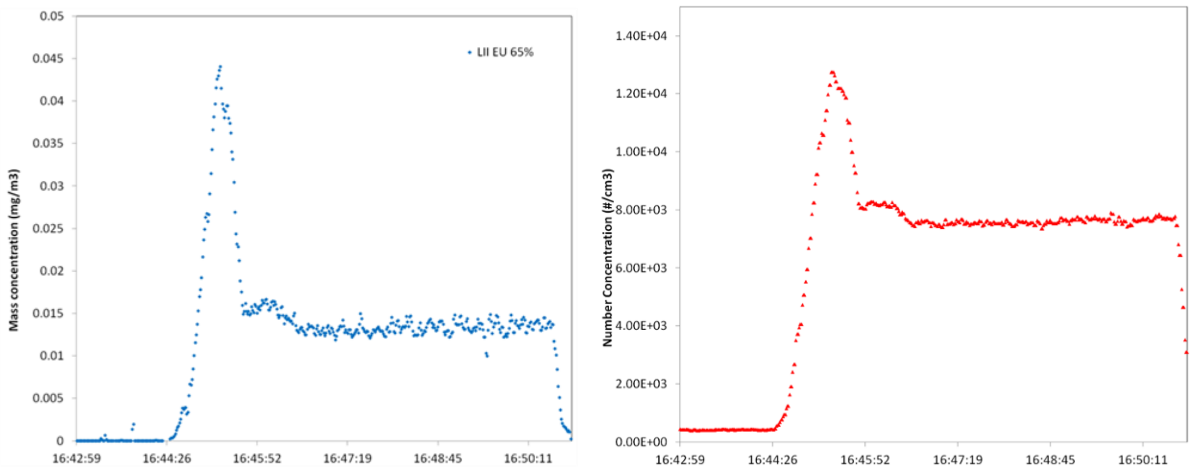


Figure 82 Stabilisation of nvPM Mass and number after acceleration from 7% to 65% Power

Performing online statistical analysis of sequential 30s averaged data periods (data averaging time as specified by AIR6241) of the above mass concentration data is shown below in Figure 83. The variability of the data within the averaged period is indicated by the 2 x standard deviation (2σ) error bars.

It is proposed that assessing whether sequential data averages $\bar{x}$ lie within 2σ of the proceeding data period. If two sequential $\bar{x}$ are within 2σ then the data can be established as being stable.

Implementation of this proposal is shown by the lower graph below. It can be seen that it takes 3 mins for the nvPM mass (LII) to stabilise.

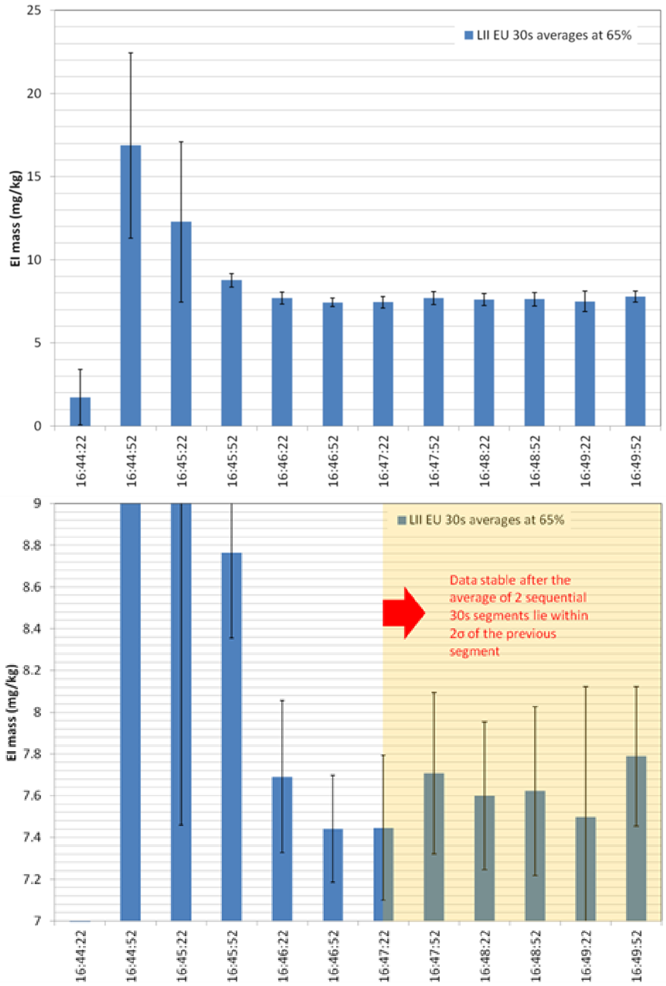


Figure 83 Stabilisation of nvPM Mass after an acceleration from 7% to 65% Power, CFM56-7B26/3, multipoint probe, 24th August 2013

The same process is shown below in Figure 84 for the number concentration. Again the average of sequential 30s data segments are compared against the standard deviation. The time for the nvPM number concentration is also in this example 3 minutes.

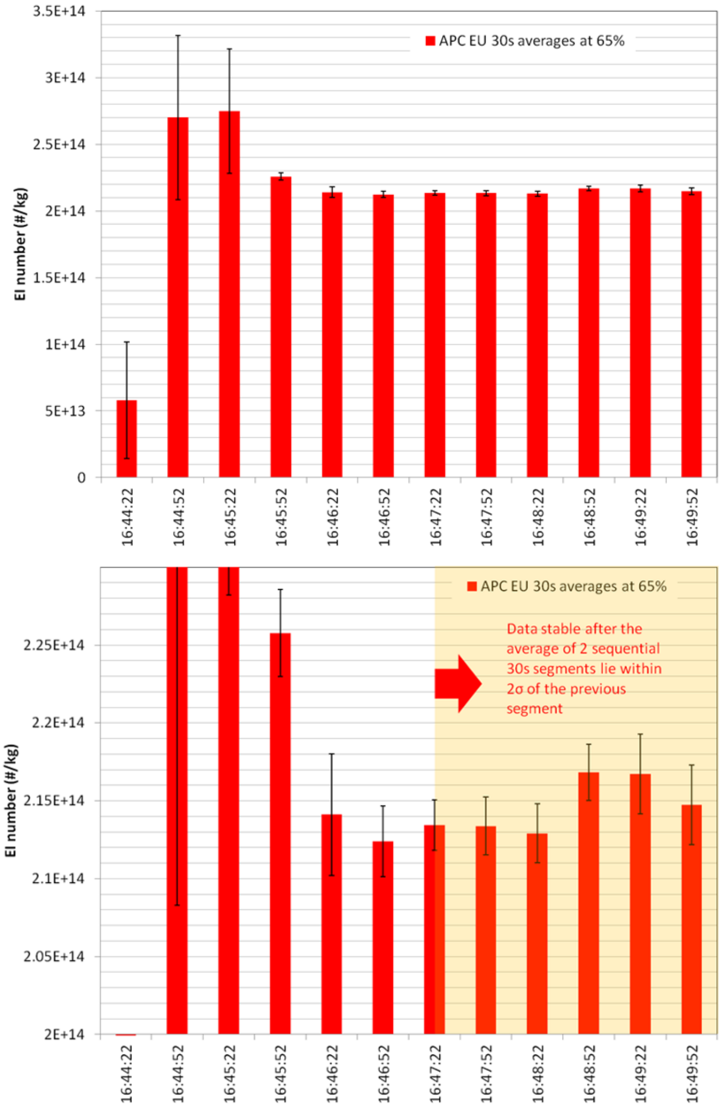


Figure 84 Stabilisation of nvPM number after an acceleration from 7% to 65% Power, CFM56-7B26/3, multipoint probe, 24th August 2013

Further assessment of multiple data points is required (during engine manufacturer testing) to see if this proposed online statistical method is successful. 3 x sequential periods maybe required or perhaps good engineering practice (human eye) is a better conventional solution.

For all the data described above in the single, dual and tri system comparisons, once the test condition was deemed stable two sequential 30s data points were obtained. In the data analysis a quality check of the data was to verify that the average of both (Emission Index) data points lay within each other's 2σ. No data points were excluded based upon this verification showing that the data points obtained in the test campaign were indeed stable. All the data included in this report is based upon the latter 30s period average.

Example EU/EASA system data for the 5th August is presented here in the graph below for both the mass Figure 85(a) and number Figure 85(b) EI's, it is observed that the average of both data points do lie within the sequential data point 2σ.

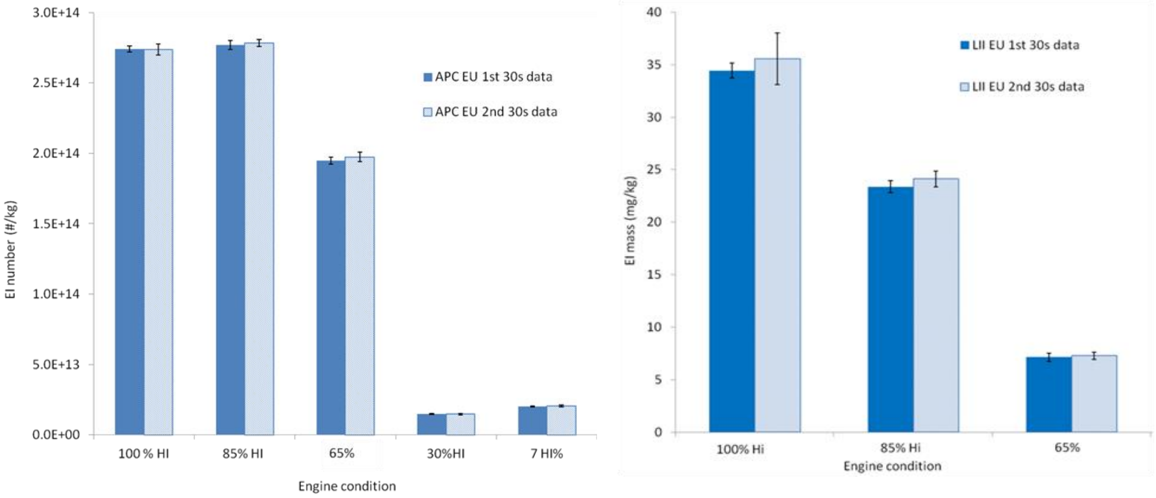


Figure 85 Non Volatile Number and Mass Stability 30 second sequential runs

In order to assess whether the nvPM signature is stable, the 'noise' quantification of the signal needs to be understood. It is unknown whether the noise in the nvPM signal is due to engine combustion variability, an effect of the sampling system or a combined effect.

By analysing σ as a % of$\bar{x}$, it can be observed whether the nvPM signal noise is constant or not. Below, this type of data is plotted for the 5th August (on the EU/EASA system) for both mass (LII) and number.

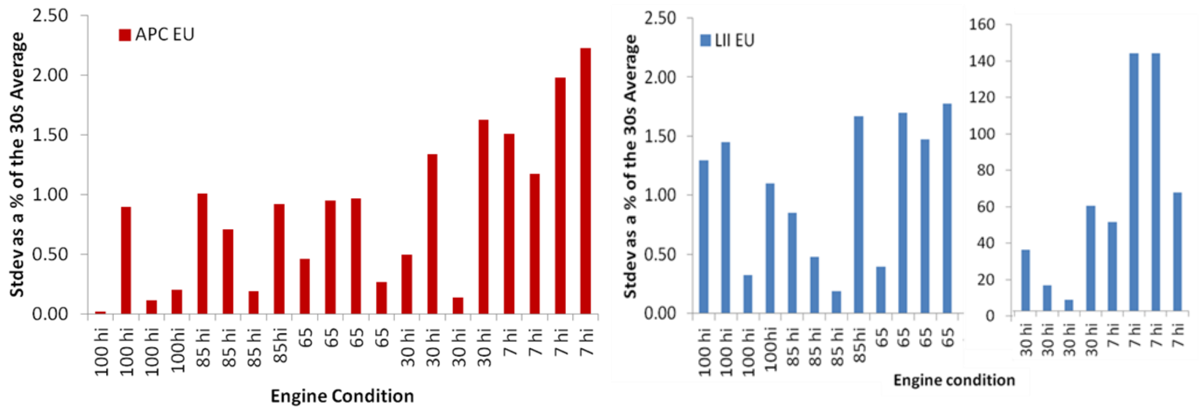


Figure 86 (a&b) Overall Stability standard deviations of 30sec averages expressed as percentage of average for non volatile number and mass respectively

It can be seen that the noise variability of the nvPM mass signal increases dramatically with reduction in engine power (and thus mass concentration); however this increase is due to the data being close to the LOD of the instrument.

For nvPM number signal, the noise also increases with reduction in engine power. It is surmised that as the size distribution shifts towards smaller sizes (at low engine powers) and the number concentration reduces, the additional sampling system losses also increase which causes larger fluctuations in the particle number concentration entering the CPC inlet.

From this data it can be expected that the noise variability for both mass and number to be within 1.5% of the average for measurements within traceable calibration. This variability is fairly small compared to other measurement uncertainties.

For the two way EU/EASA-Swiss system comparison, the maximum continuous condition (defined as TP0) was included as part of the engine test schedule. The previous weekend the Swiss certification-like engine test had observed large mass concentration spikes at this test point.

The graph below shows the mass and number concentrations during the max continuous condition (with prior 100% condition and deceleration to idle afterwards). Large instabilities/spikes can clearly be seen in all the mass instruments in both sampling systems. Whereas in the number instrument there are no spikes/instabilities at all (note that the Swiss APC also observed no spikes).

This indicates that the spikes are probably clusters of large particles. Due to the cyclone in each system removing particles >1 micron prior to the instruments, they are likely several 100nm in diameter. The source of these large particles is most likely due to particle shedding inside the multipoint probe as the spikes are not observed during single point probe measurements, the spike frequency reduced over time and this type of particle is an unknown combustion phenomenon. Apart from potentially having an impact on measured mass data (if spikes occurred during the 30s average), there could also be an impact on system operation if the large particles caused blockage especially at the primary diluter inlet nozzle.

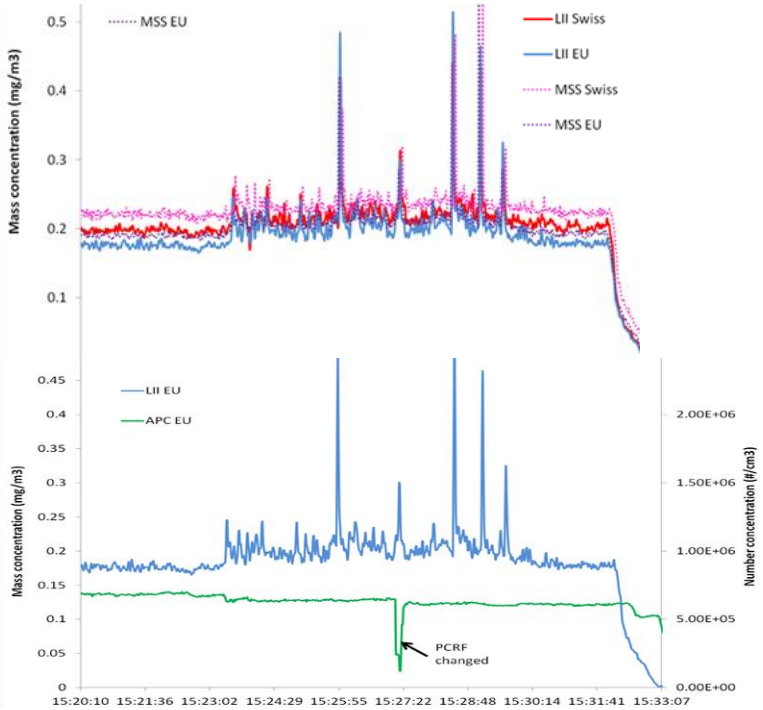


Figure 87 Mass stability two system inter-comparison from CFM567B26/3, using multipoint probe, 24th August 2013

On the 25th August (single system test) an FMPS was attached to the make-up flow line of the EU/EASA system to measure real-time particle size distribution in an attempt to observe what size particles were causing the spikes.

In the graphs below the time line shows again large spikes in the mass measurement but not the number measurement. However, this time the spike frequency is much less. This could be because most of the particles coated on the inside of the multipoint probe were shaken off on the previous day running (at max continuous the probe vibration was very high – as noted by SR Technic's engine operators). The instability circled in red corresponds to the red vertical lines timestamp on the FMPS size distribution contour plot (Figure 88). It is observed in the contour plot that there is no evidence of instability at any of the detected particle sizes 5 to 500nm at the concentration sensitivity of the instrument (~100#/cc at 500nm). It is therefore likely that the large carbon particles are indeed several 100 nm in diameter.

If further investigations of large spikes are required in the future, it is recommended that an OPC (Optical Particle Counter) or ELPI (Electrostatic Low Pressure Impactor) are used to assess the particle size as they operate from ~0.2 to several microns and can measure single count particles at 1Hz frequency (same as LII & MSS).

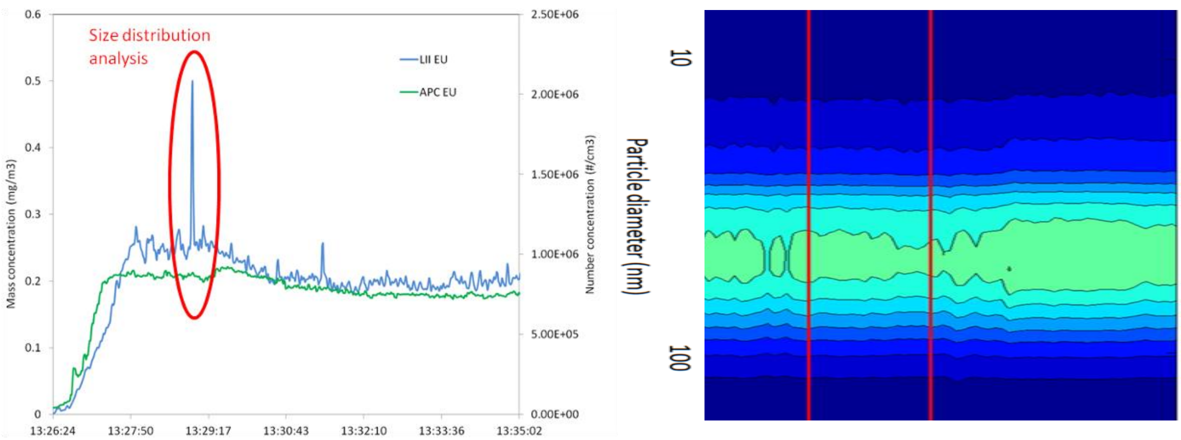


Figure 88 (a&b) nvPM mass/number and size contour map from TSI FMPS for time period of large mass instabilities from CFM567B26/3, using multipoint probe, 25th August 2013

7.3.10 Online measurement of VPR Dilution Factor (DF2) via gaseous measurement

AIR6241 currently allows two options to determine DF2 (dilution factor within VPR), either by using the manufacturers factory calibration value (which is checked that it is within 10% via the VPR DF check procedure) or by gaseous (CO_2) determination (similar to that already prescribed for DF1). SAE E31 has queried whether both options are required for the PM ARP, but further data was required to understand the uncertainties involved in both options.

To measure CO_2 downstream of the VPR requires a low range gas analyser (FS 100ppm or 50ppm) that meets the performance specifications of ARP1256. The Signal Instruments NDIR gas correlation low range CO_2 analyser, installed in the EU/EASA reference system, surpassed these specifications.

Comparisons were made of DF2 on a specific engine target condition between the online CO_2 measurement and the instrument dilution setting (PCRF label). The EI number was calculated for both options and is presented in Figure 89 below. The experiment was repeated (noting that engine conditions may not be identical due to changes in ambient conditions) and can be seen by the two labels next to each other. There is no clear trend between using either option. Though when plotting % difference between them (Figure 90) it can be observed that at only one engine test condition did the VPR instrument DF2 read higher than the CO_2 derived factor. In fact Figure 90 shows that at all times both measurement options were within 10% of each other.

Successful online DF2 measurements via CO_2 were performed and no significant differences were observed between online DF2 and instrument derived values (variance was within AIR6241 10% allowance specification for the VPR DF check).

However, it should be noted that the online gaseous methodology could be improved if the CO_2 analyser and calibration gas specifications were improved beyond ARP1256 requirements. For example, linearity 1% of reading and 1% calibration span gas.

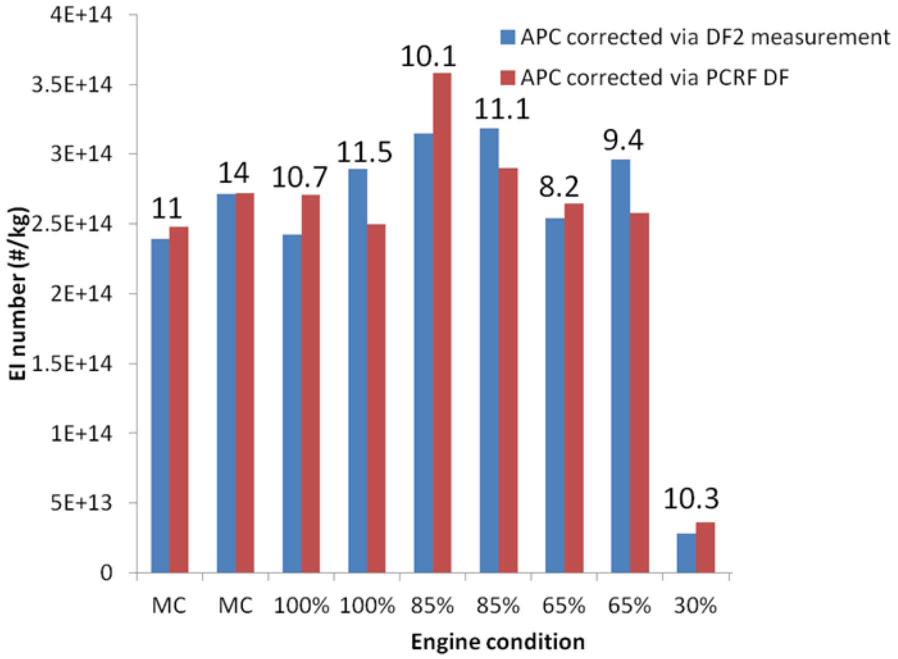


Figure 89 Variation in EI number using PCRF versus online CO_2 measurement, the figures above the columns represent the DF1 variability between the measurement points.

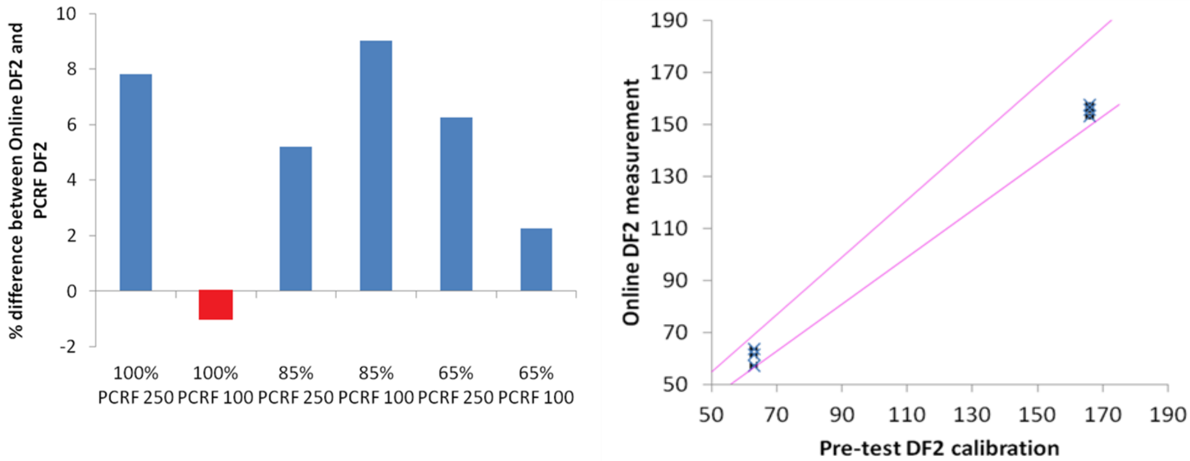


Figure 90 Percentage differences observed between on line gaseous determination of VPR dilution factor and pre-test dilution factor checks (pink lines determine 10% allowance in AIR6241)

7.4 AIR 6241 Operability

The EU/EASA reference system was operated in accordance with AIR6241 throughout engine testing. In addition, to help with the operation and test planning the draft standard operating procedure (SOP) created by the SAE E31 team leads in October 2012 was also used. Though some aspects of the SOP have been superseded by AIR6241, it is a useful document and should be updated to reflect the AIR6241 specifications in order to help simplify engine manufacturers operation their own nvPM systems.

During the engine test campaign some observations on the operability of the nvPM system were discovered and are discussed below.

7.4.1 Pre & Post Test Cleanliness Check

As defined by AIR 6241 it is necessary to prove the cleanliness of your sampling system (and ensure there are no leaks) by closing the inlet to the primary diluter thus only allowing HEPA filtered diluents into the sampling line. The check is deemed successful if the nvPM number counter reads a 3 minute average count of less than 0.5 particles/cm^3 at all the DF2 settings. To ensure that the system was at conditions comparable to that at operation the make-up pumps and analysers were run at flow rates used during testing which reduced the pressure in the sampling line to sub-atmospheric.

It was observed during testing that the cleanliness check could only be achieved at pressures greater than 900mbar on both the EU/EASA and North American mobile reference systems which suggested, that there was a leak in both the sampling systems. After checking each joint within the sampling train the background count did not improve in either system, which led the teams to suggest that the leak was occurring within the AVL APC unit. In order to confirm this hypothesis, the AVL APC was disconnected from the sampling line and connected in series with a throttling valve to a HEPA filter. It was observed that as the pressure was decreased the particle count increased confirming that the leak came from within the APC.

It was decided to experimentally determine the leak rate versus sample inlet pressure. Ascertaining a level that could be reached for a leak check would help to advise SAE E31 whether a tolerable background count at 0.5 particles/cm^3 was too difficult to attain. Details of the findings are presented in Figure 91.

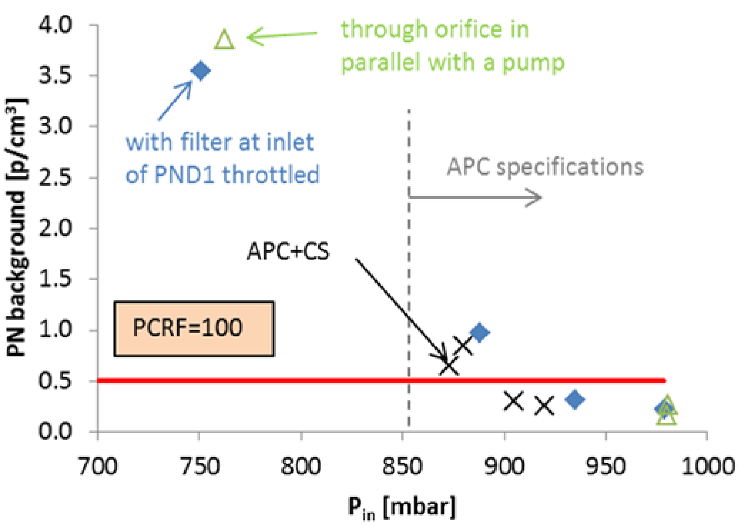


Figure 91 Results of cleanliness check of EU/EASA Mobile reference AVL APC, on sampling line and through throttled HEPA filter and historic AVL data

As can be seen it is observed that for an inlet pressure to the AVL APC of less than 900mbar the current AIR6241 cannot be met by the AVL APC even if filtering from a HEPA filter (blue diamonds). It is also noted that comparable overall background counts are witnessed when the AVL APC is sampling normally through the entire sampling system (black crosses) which implies there were no additional cleanliness issues or leaks in the EU/EASA mobile reference system. When AVL representatives were approached regarding this issue they were able to supply further historical data for the original concept APC which has been added to the graph (green triangles) and also indicated that the leak was likely occurring in the rotating diluter due to the sealing arrangement. This agreement shows that the issue is not related with the additional catalytic stripper added to the AIR 6241 compliant AVL APC. The 0.5particle/cm^3 threshold is witnessed at pressures representative of line pressures during sampling, thus it is suggested to SAE E31 that they consider increasing this threshold prior to the ARP being published.

As currently the CPC specifications only cover traceable calibration down to 2000particles/cm^3 and a 10% linearity uncertainty at this point is currently deemed acceptable it is felt by the authors that even increasing the permissible count to 5particles/cm^3 would only add an additional 0.25% uncertainty to the lowest calibrated point which is well inside the currently acceptable 10% uncertainty.

As mentioned earlier in the AVL APC calibration section (6.4.1.1) due to an error in the manufacturer's calibration procedure the EU/EASA mobile reference system catalytic stripper had been set to 300°C. To meet compliance with AIR 6241 the catalytic stripper temperature was increased to 350°C prior to engine testing. After this was done a further cleanliness check was performed and it was noted that there was a distinct rise in particle count on what seemed to be a regular frequency. On investigation of the instrument on-board service log files, it was noticed that the increase in number coincided with the catalytic stripper heater demand. It was observed that the AVL APC temperature control allowed a reduction in catalytic stripper temperature in the order of 10°C before loading the heating element again, by which time particles started to be counted by the CPC until the heater demand was again removed by the control unit, at which time the particle count would again drop. A schematic representation of the phenomena is given below in Figure 92.

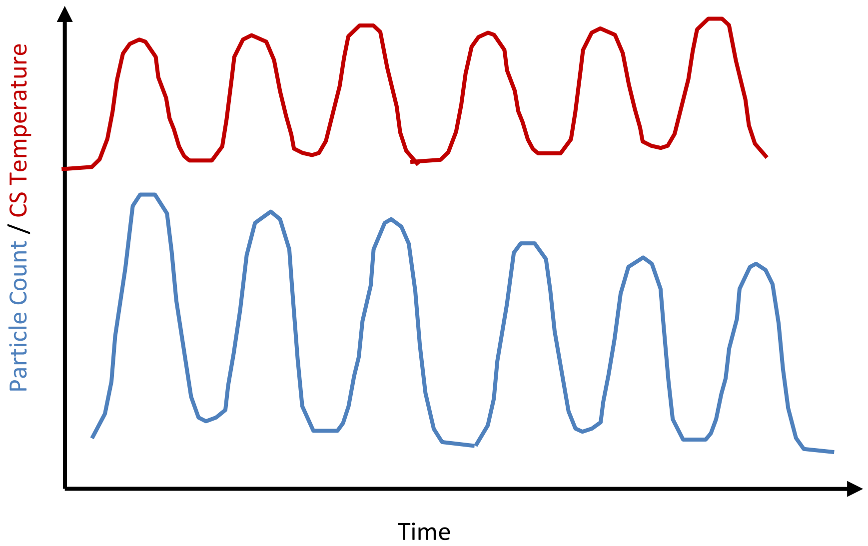


Figure 92 Schematic representation of particle generation in catalytic stripper

As depicted above it was observed that over time the maximum particle count being observed was reducing. Thus in consultation of an AVL representative it was decided to turn up the catalytic temperature to 365°C and leave overnight so that the new cycling temperatures were greater than the 350°C set point required the next day for testing. On investigation the next day it was observed that this particle cycle phenomena had disappeared. During the test campaign the APC was left in a standby mode so the heater to the catalytic stripper always remained on to attempt to try and stop this occurrence of cyclic particle counts occurring again.

7.4.2 Observation of AVL APC Exhaust Geometry Sensitivity

In order to measure online the secondary VPR dilution, the AVL APC exhaust was used to provide sample (via a forwarding pump set at 1.5 slpm) to the CO_2 analyser. Due to the additional internal APC dilution, approximately 9 slpm of exhaust is emitted from the instrument. Thus there should be plenty of flow available for the gas analyser.

The APC exhaust is closely connected to the CPC inlet and any changes of backpressure will affect the CPC operation (instrument is very sensitive to changes in inlet pressure). AVL personnel recommended adding a length of tube to the analyser to prevent any impact of pressure changes at the point where the flow splits to go to the CO_2 analyser affecting the number concentration.

During the initial engine testing on the 25th, an experiment (at engine condition 85%) was performed to check that sampling exhaust from the APC was not affecting the CPC number concentration. It can be seen in Figure 93 that when the extra 30cm tube was removed, the number concentration decreased by approximately 7%. This effect appeared to be due to the additional sampling tube and CO_2 measurement flow affecting the CPC inlet pressure.

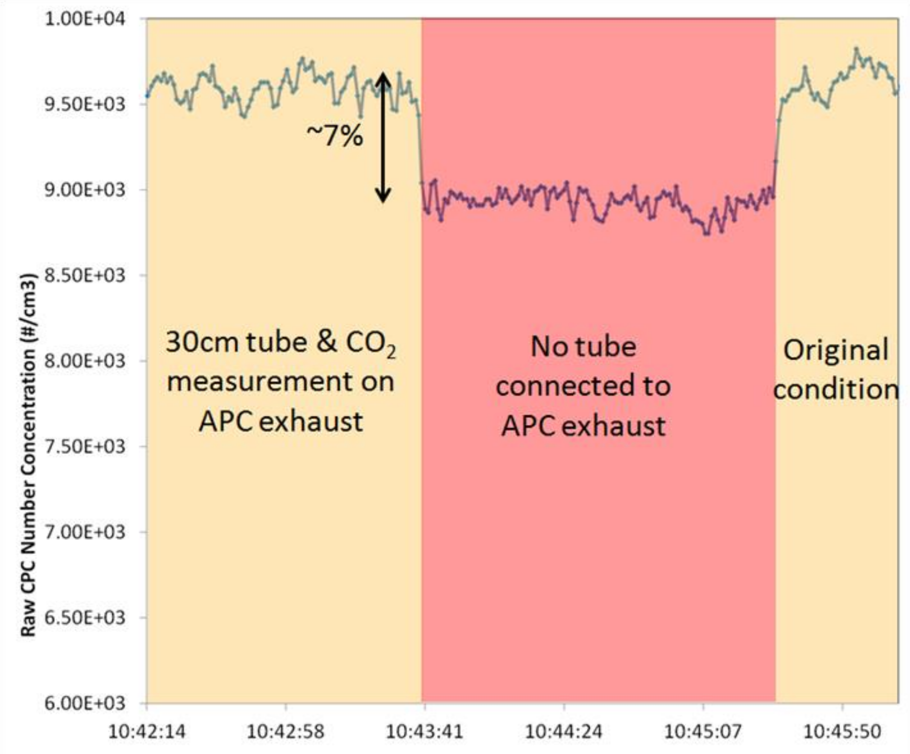


Figure 93 Number concentration impact of additional sampling and exhaust line on APC exhaust

A number of different tube geometries were implemented to understand what was possible to achieve as a sampling geometry (i.e. no effect on CPC inlet pressure). These are shown in Figure 94 below together with whether a difference was observed.

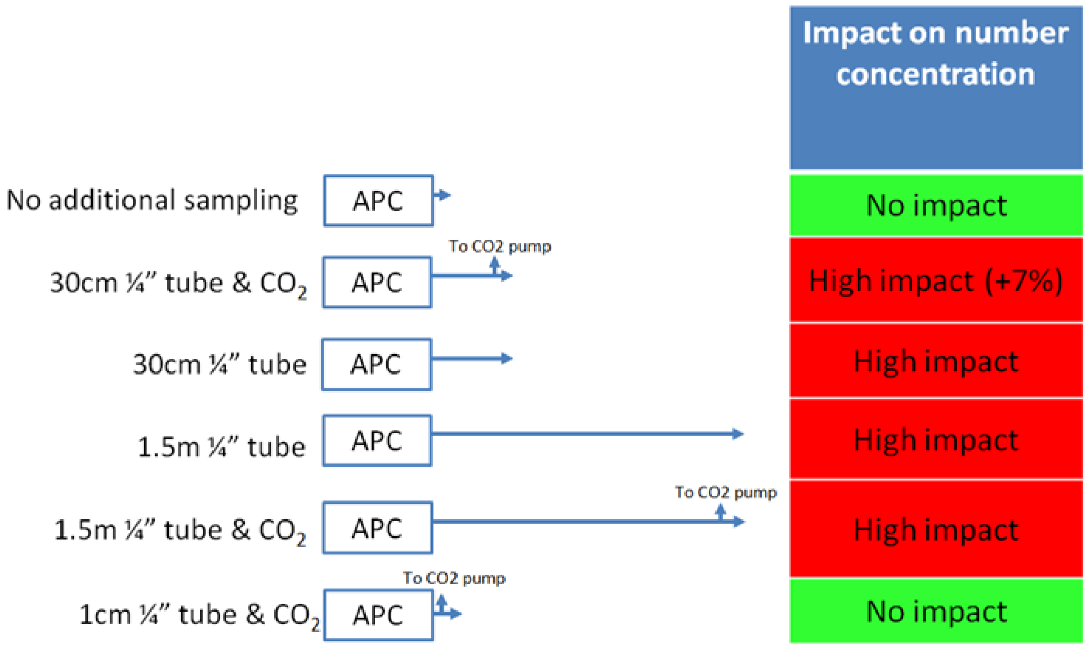


Figure 94 Schematic diagram showing different APC exhaust configurations together with the impact on number concentration (High impact means increased number concentration)

The only CO_2 sampling geometry which equalled that of no additional sampling/tubing was with the flow split directly at the instrument exhaust and no additional tubing. Therefore this configuration was used for the remainder of the engine test to be consistent with the rest of the test campaign.

Following the SR Technics test campaign, discussions with AVL took place on this unexpected observation. AVL undertook a series of detailed laboratory experiments and were unable to reproduce the effect, proving that the AVL APC is immune to downstream pressure variations from additional sampling geometry. The AVL experiment report is reproduced in Appendix 10.5. In addition, during the small engine testing, described in Task 4, the consortium attempted to replicate the APC exhaust geometry effect observations with also no success.

The CPC concentration deviations observed at the SR Technics test campaign could be attributed to another reason (still unknown), but not to the geometry of the APC outlet.

7.4.3 Dilution Factor Variability

In AIR 6241 it is stated that the first dilution factor (DF1), occurring in the primary dilutor (3PTS) should be in a range of 8-13 (dilution ratio 7-12). It has been shown in previous studies that numerous factors including inlet pressure, diluent pressure and exhaust geometry affect the dilution factor observed in eductor dilutors.

In an attempt to try and keep DF1 as stable as possible and within the AIR6241 specifications, the spill line, diluent pressure was used during the single system testing (noting that the certification-like probe was installed thus the experiment was an appropriate test for OEM-type probe geometry). The VPR dilution settings were changed as appropriate to keep the CPC in single count mode in the traceable calibration range (where possible). The DF1 variability across the engine test conditions can be seen in Figure 95 below. For the majority of cases it was possible to stay within 10±1 DF1 except for one of the low power conditions (7%). It should be noted that for the 7% case it was not attempted to control DF1. The authors feel that it would have been possible to reduce DF1 into the required range by reducing the diluent pressure.

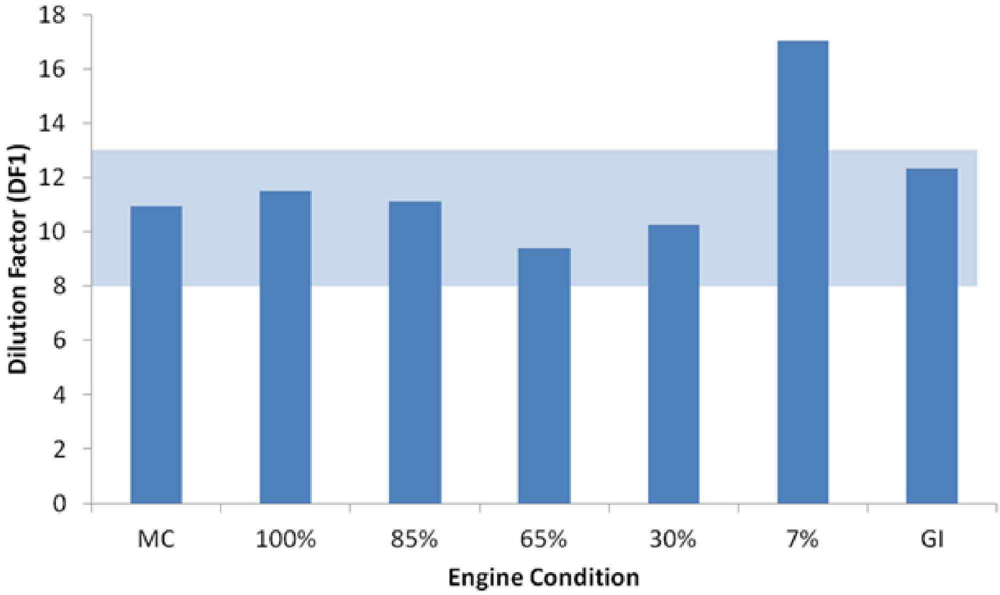


Figure 95 Certification-Like Single System Testing Dilution factor variation of reference system 25th August 2013

It is recommended for the ARP that specific system operations are indicated to help the operator decrease DF1 at low engine powers, namely:

1) Close the spill valve when the diluter1 inlet pressure is low/sub-ambient
2) Decrease the diluent pressure (noting to ensure that the pressure is not decreased too far that ambient particles leak into the system through the diluter1 vent; for Dekati DI1000 a diluent pressure of 1.5bar was appropriate)
3) Reduce GTS/Annex16 line flow rate to minimum, noting that this may mean that the 3s residence time criterion in the probe/2PTS section may not be achievable.

At higher powers DF1 may need to be increased (to ensure the CPC is within traceable calibration range):

1) Open the spill valve when diluter1 inlet pressure is high/above ambient
2) Increase the diluent pressure (noting to ensure that the pressure is not increased too far so that only diluent enters 4PTS; for Dekati DI1000 a diluent pressure of 4 to 4.5 bar was appropriate)
3) Increase GTS/Annex16 line flow rate

When operating reference systems simultaneously in parallel, it is witnessed that the additional flow caused by the additional sampling lines and spill lines can cause reduced pressures at the additional splitter (2PTSa). As the separate systems are working in isolation, each spilling independently and controlling its GTS (current Annex 16) line at different flows to match the residence time criterion, it is possible that the inlet pressures to each systems primary diluter can be subtly different. Together with variations in the delivery pressure of the diluent gas can lead to differences in the primary dilution factor of each line. For this experimental setup it was decided to set up each of the systems as they would run if running individually (only controlling their individual spill) and ascertain whether the systems stayed within the prescribed dilution factor specification.

It can be seen below (Figure 96) that when operating the EU/EASA and Swiss reference systems in parallel on the multipoint probe (12 x orifii open), it was possible to maintain DF1 within the 8 to 13 AIR limits for all engine conditions except for the 7% target.

It is unknown why the Swiss DF1 is so much lower than the EU/EASA system. One possible cause could be the cleanliness of diluter1 (note that the Swiss diluter was cleaned just prior to the 24th August engine testing). This cleanliness issue needs to be discussed prior to the ARP.

Note that in SAMPLEIII SC02 Zurich test campaign the same discrepancy occurred with the SAMPLEIII system DF1 always being higher than the Empa/FOCA system. In the conclusions for that work it was considered that perhaps the splitter1 on the SAMPLEIII system was causing the difference. However, with the EU/EASA system redesign of splitter1 to be nominally identical to the Swiss and North American reference systems (inlet and spill ID equal to GTS and PTS ID), this can now be seen not to be the cause of the discrepancy.

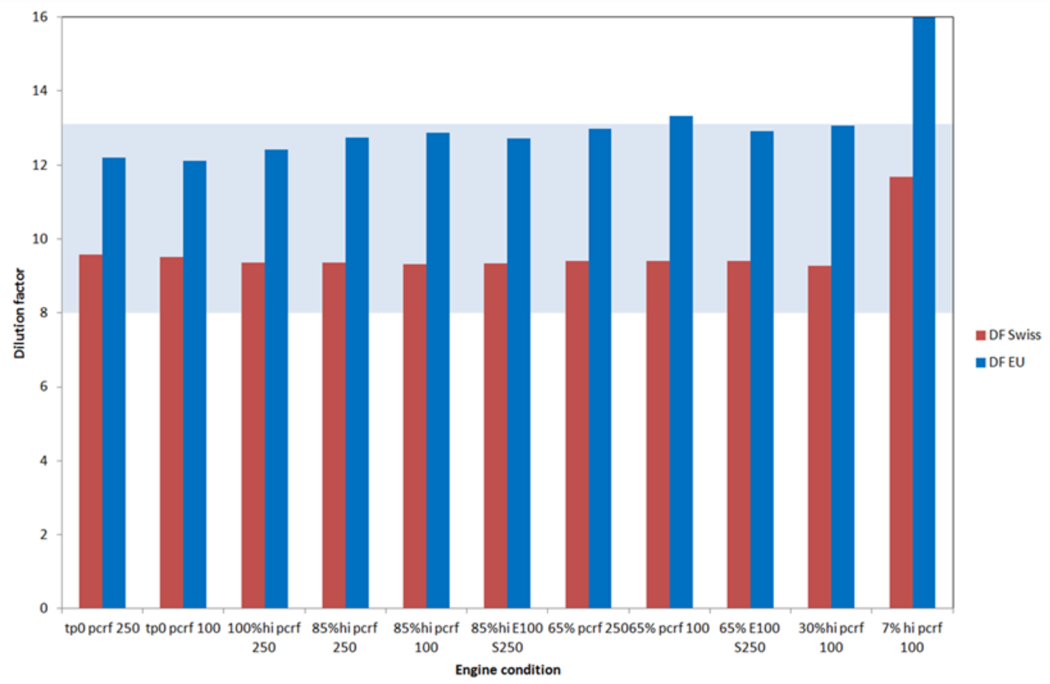


Figure 96 Two Way Inter-comparison Dilution factor variation of reference systems 24th August 2013

The multi-day three way reference system comparisons between the EU/EASA, Swiss and North American systems took place using the single point probe which had a larger inlet area than the combined area of the multipoint probe. This helped to provide a higher sample flow rate at low engine power than the multipoint. The results shown below from the different test runs show that again the issue of staying within the AIR6241 range is most difficult at low engine powers (low dynamic pressure at probe inlet) even with the larger probe inlet area. The DF variability results show a common pattern across all the test runs. As a reminder the North American system does not measure raw CO_2 and the North American data is presented corrected (DF1) using the EU/EASA raw CO_2 data (therefore differences in raw CO_2 will not be present in DF1 data comparisons between EU/EASA and North American systems).

The EU/EASA and North American systems had similar DF1 at high engine powers but as the engine power decreased, the North American system DF1 increased at a faster rate than the EU/EASA DF1, such that the North American system was outside the prescribed range even at 65% power condition. It should be noted that the GTS flow rates on the EU/EASA and North American system were identical, namely 10 slpm at high engine powers and 1.5 slpm at low engine powers (30% and below). However, due to the additional gas analysers on the Swiss system, the minimum sample flow-rate on the GTS they could achieve at low engine powers was 6 slpm. As both the EU/EASA and North American systems had their flow-rates being operated in an identical manner it is unknown why DF1 is moderately higher on the North American system.

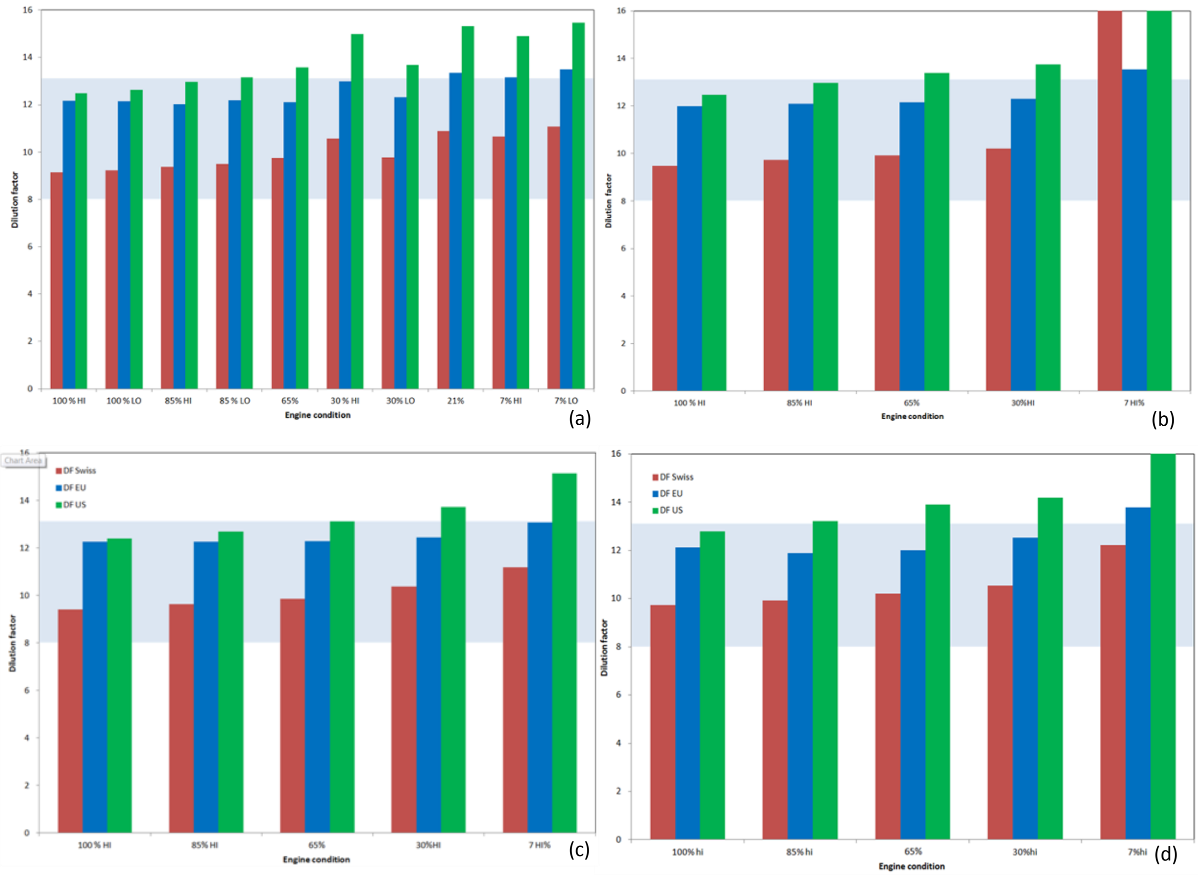


Figure 97 (a-d) 3 Way Inter-comparison Dilution factor variation of reference systems for the 3rd, 4th morning, 4th afternoon (EU/EASA system N_2) & 5th August 2013 respectively

The Swiss DF1 is consistently much lower than both the EU/EASA and North American systems. This could be due to a number of reasons:

1) Different Diluter1 vent geometry. Additional backpressure on the diluter exhaust - the Swiss vent is large bore (>12 mm) and very short (few cm), EU/EASA system is full bore (12 mm) and approximately 30cm in length, the North American system is 7.7mm bore and approximately 20 cm in length.
2) Diluter1 cleanliness. Without frequent checking it is unknown if there is any build-up of soot inside the diluter nozzle which could change the diluter flow dynamics
3) Generally additional GTS flow rate in the Swiss system (due to extra gas analysers) may have caused a localised lower pressure at the 2PTSa splitter leg inlets to the EU/EASA and North American systems (and therefore at the inlet of the subsequent diluters).
4) Or an unknown reason.

Overall, whether on single, dual or tri system comparison, the DF1 variability was predominantly within the specified AIR6241 range. On the single system it was possible to operate other parts of the sampling system to ensure DF1 range compliance. On multi-system comparisons this was not performed and it may mean that the AIR6241 allowable DF1 range needs to be increased slightly when system comparison testing is performed in the future.

In addition with keeping DF1 in the required range, the spill line and VPR dilution were used to try and keep the number counter within its calibrated range of 2000-10,000 particles/cm^3 and also keep the mass analysers above 3x their lower detection limit (LOD) ~10ug/m3. However, this was not possible at lower power conditions (30% and below). This raises several issues which will be put forward to the SAE E31,

1) At present AIR 6241 does not recommend a lower count value for the CPC but only at which points it is to be calibrated, as such it could be perceived that the AIR allows the counting analyser to be used outside of its traceably calibrated range, which is an issue that needs to be debated before the publication of the ARP.
2) Current in-service modern engines are already at the LOD for the mass measurement. Feedback from ICAO/CAEP/WG3/PMTG is required on this subject. However, it needs to be discussed in E31 whether techniques to traceably calibrate mass instruments at very low mass concentrations need to be pursued or whether measurements on the raw GTS line are acceptable.
3) Impact on line loss correction methodology. (theoretical size distribution calculation) If the mass concentration is not known (below the LOD) then it is impossible to calculate theoretical size distribution and therefore diffusion loss correction for the number concentration (though it is still possible to calculate thermophoretic loss correction).

7.5 Conclusions of Task 3

1. An EU/EASA mobile reference system was constructed in compliance with both AIR6241 and SAE E31 recommendations for a non-volatile PM reference system
2. Three AIR6241 compliant systems, 2 mobile (EU/EASA and North American) and 1 fixed (Swiss) were successfully inter-compared (to be known as ‘reference’ systems) on a CFM56-7B26/3 engine PM source.
3. Long term inter-comparability of compliant reference systems is needed.
4. AIR6241 Primary Dilution Factor (DF1) range limits were met for the EU/EASA system across all CFM56-7B26/3 engine conditions during the Zurich testing. This was achieved by controlling the diluent pressure and spill valve position upstream of Diluter 1.
5. It was not always possible with the EU/EASA reference system to keep the GTS flow rates within existing Annex 16 specifications, whilst ensuring DF1 was in AIR 6241 specification. This was particularly observed at low engine power, thus simultaneous gas, smoke and nvPM measurements would not be possible with the Zurich probe geometry tested.
6. Discrepancies were observed in the three reference systems for DF1 during the multiple system testing. Typically the Swiss system was significantly lower than the EU/EASA system and the North American system slightly higher (sometimes outside the AIR6241 specified range). However the effect of simultaneous sampling of

multiple systems will have had an effect on DF1 compared to what may be achieved during single system testing.

7. During the AIR6241 system cleanliness (and leak) checks the mass instruments met specification; however, the number specification was unable to be met (on both the EU/EASA and North American systems). It was proven that the rotary diluter seals of the AVL APC were the leak source, the cause being the lower APC inlet sample pressure witnessed on both the EU/EASA and North American system compared to the Swiss system.
   – Recommend that the AIR6241 zero limit be increased at least as a minimum from 0.5 to 1 particles/cm^3 (for the lowest DF2 used for the measurement), noting that at even at 5 particles/cm^3 the additional uncertainty would only be 0.25% when compared to the AIR6241 existing traceable CPC calibration range.
8. Ambient mass and number data was obtained as per AIR6241 specifications. However, there is inconsistency in the length of time required by AIR6241 for ambient (and zero) measurements (3 minutes) compared to engine measurements (30s)
9. During the VPR performance check, it was observed that there was a small impact of inlet sample pressure on the measured Dilution Factor (DF). The instrument dilution settings were only just within the AIR6241 10% limits. At this time it is unknown why the DF measured during the performance check were different to those quoted during the calibration certification. As such the authors recommend that:
   – The VPR performance check is conducted at a sample inlet pressure condition representative of system operation.
   – During future system measurements, the VPR DF check is monitored over time to check for long term drift.
10. It was observed that PM data took numerous minutes to stabilise, (typically ~2 to 4 minutes) after the engine reached a new power condition. The judgement for stable emissions conditions has historically always been performed by visual assessment of real time gaseous data. However, an expression using 2 standard deviations is proposed as a possible candidate for verifying w a data-point stable. The authors thus recommend.
    – SAE E31 should consider whether visual observation or a mathematical expression should be used to verify PM stability.
11. Large spikes in mass concentration were observed at the maximum continuous engine condition, on the ‘multi-point’ cruciform probe. These spikes were attributed to ‘particle shedding’ (similar to observations in SAMPLE I rig measurements) from the internal probe surfaces.
12. It was observed that the nvPM number concentration could vary during the evaporation tube/ CS heating cycle. Therefore the authors recommend
    – Pre-heating the evaporation tube / catalytic stripper to at least 360°C for several hours after receiving the instrument back from calibration, before cooling back to 350°C.
13. No impact of DF1 sensitivity was observed on the CFM56-7B26/3 engine over a range of engine power conditions.
14. Neither the nvPM mass or number concentrations were statistically sensitive to DF1 diluent composition (Synthetic Air or Nitrogen)
15. Successful online DF2 measurements via CO_2 were performed. No significant differences were observed between online DF2 and pre-test DF2 check values

(variance was within AIR6241 10% allowance specification for the VPR DF check). The authors note that the online methodology could be improved if the CO_2 analyser and calibration gas specifications were improved beyond ARP1256 requirements.

16. Careful consideration of downstream CO_2 (or other ancillary PM instrument) sampling geometry from APC is required. Any small pressure fluctuation on the instrument exhaust was shown to alter the CPC number concentration.
17. The 3 reference PM number instruments were sent to the instrument manufacturer for calibration in accordance to AIR6241 specifications, as a result instrument penetration limits needed to be reduced by the SAE E31 prior to the final document ballot, in order to meet conformance.
18. During the reference nvPM instruments annual calibrations, several calibration issues were encountered at the (ISO 17025 compliant) qualified calibration laboratory. As such the only VPR/CPC in full AIR6241 compliance was the North American system. Therefore the authors recommend:
    - VPR/CPC suppliers develop a specific aviation specification calibration certificate. This should include close liaison with SAE E31 to produce a recommended calibration procedure/certificate.
19. Significant differences were observed between the EU/EASA and the other two reference CPC linearity gradients. It is noted that the North American and Swiss CPC's were calibrated concurrently and all CPC's are of the same model. It was observed that all the reference CPC displayed increased offset from linearity at the lowest traceable number limit (2000 particles/cm^3). Non-linearity is not expected therefore the authors recommend:
    - That further work (to include CPC manufacturers) is performed to assess whether the 10% linearity limit can be tightened towards 3 or 4%.
20. The CPC lower size cut-points (at D_{10} & D_{50}) were significantly different between the EU/EASA and other two reference systems, again it is noted that the North American and Swiss CPC's were calibrated concurrently and all CPC's are the same model. It is thus recommended:
    - CPC calibrated lower size cut-points (D_{10} & D_{50}) are included in a possible future PM system continuous loss function correction.
21. It was observed that altering the PCRF setting of the VPR changed the dilution corrected number concentration, though the variance was within the overall number measurement expected uncertainty, but did always move the measured number in the same direction. Therefore it is recommended:
    - That where possible on future PM system engine testing, an evaluation of different dilution settings should be performed at steady engine condition(s) to ensure that the variance stays within the expected measurement uncertainty.
22. At engine powers of 30% and below, it was not possible to operate the system at a combined (DF1 plus DF2) dilution factor so that the PM number measurement (CPC raw count) was in the AIR6241 traceably calibrated range. Therefore it is recommended that:
    - Investigate implementation of a traceable calibration methodology for <2000 particles/cm^3. For example, ISO 27891 Annex I (in final draft expect to be published 2014)
    - And/or assess the increase in number measurement uncertainty measurements if nvPM number counts are obtained below the traceable limit.
    - Investigate if commercially available VPR's could be converted to provide a lower DF2.

23. Overall the number measurement reproducibility between the 3 reference systems was generally within theoretical measurement uncertainty predictions (18 to 22%); However these 3 units were nominally identical so the uncertainty permitted by AIR 6241 may be higher than this.
24. Various biased discrepancies between the 3 systems were observed which should be further investigated, as the observed number data contradicted pre-test miniCAST comparisons. Therefore the authors recommend
    - System inter-comparisons are performed between different PM number instrument manufacturers (VPR and CPC).
    - system PM instrumentation are operated under environmental conditions recommended by manufacturers
25. All PM mass instrumentation met AIR6241 calibration performance specifications
26. It was observed that utilising diaphragm pumps in EU/EASA and North American systems caused the AVL MSS instrument to experience significant noise interference, caused by fluctuations in the sample pressure. It was noted that noise was not observed on the Swiss MSS due to the use of a buffer volume upstream of the make-up flow pump, thus this methodology was applied to both the North American and EU/EASA reference systems. It is thus recommended:
    - That AIR6241 instrumentation and make-up pumps specification should either limit the type of pump utilised, or control pressure fluctuations using damping volumes if an MSS is utilised in the PM measurement system. If the pressure fluctuation impact limit is known for the MSS, a performance based sampling specification could be implemented instead.
27. The AVL MSS must be run in service mode to obtain PM mass measurements on an AIR6241 compliant system if the instrument inlet pressure is lower than -80 mbarG (as observed on both the EU/EASA and North American systems). The MSS can only be used in normal conventional standard operation at instrument inlet pressures higher than -80 mbarG.
28. On Pre and Post engine test miniCAST comparisons, all the mass instruments agreed within measurement uncertainty expectations (11%).
29. Deviations larger than uncertainty expectations were observed between the mass instruments on engine PM inter-comparisons. Initial estimates of AIR6241 mass methodology uncertainty could be as large as 40 to 60% at low (<100 $\mu g/m^3$ mass instrument inlet concentrations), which reduces to ~20% at higher (>100 $\mu g/m^3$ mass instrument inlet concentrations).
30. There is some evidence that similar mass instrument types (LII vs MSS) agree better than comparing different methodologies.
31. The discrepancies observed between the PM sources (gas turbine engine and miniCAST) are under further investigation by the SAE E31 mass team including AVL.
32. At CFM56-7B26/3 engine powers of 30% and below, the mass concentration at the instrument inlet was below the AIR6241 specified 3xLOD (9 $\mu g/m^3$).
    - Require feedback from CAEP to assess whether to spend additional technical time and resource to achieve PM mass measurements at lower engine powers.
    - Operate/calibrate mass instrumentation below the existing AIR6241 LOD.
    - Possibly re-investigate feasibility of nvPM mass measurement on the GTS line
33. Representative PM data was obtained from the CFM56-7B26/3 engine. nvPM EI and size distribution data was consistent with previous PM trends observed in typical modern ‘rich burn’ engine tests in SAMPLE I, II & III campaigns. The maximum EI

mass (~75 mg/kg) and largest mean particle sizes (~45 nm) were observed at the highest engine conditions. The maximum EI number (~3e14 #/kg) was observed at high powers but not at the highest. Both the lowest EI mass (which was below LOD <0.1 mg/kg) and EI number (~2.1E13) #/kg) were observed at engine conditions slightly above ground idle and had the smallest mean particle sizes (~16 nm). The EI number and EI mass increased slightly at ground idle conditions. As in line with AIR6241, these EI's are not corrected for particle loss in the system.

8. Task 4: Acquisition and analysis of additional engine data

8.1 Introduction

To support both the nvPM CAEP and E31 process, the consortium were tasked with acquiring data from aircraft engines at Rolls-Royce in conjunction with the Rolls-Royce AIR6241 compliant system.

Unfortunately no Rolls-Royce large engine emission tests were available within the short timescale between the Zurich engine testing and the end of the SAMPLEIII SC03 contract (2 months). Thus alternatively the opportunity was taken to obtain measurements on a small in-service engine instead. This had the benefit of being able to perform a bespoke engine test schedule allowing repeated and long test points. In addition further data was obtained to help address the dilution factor sensitivity technical issue (as discussed above in section 7.3.8); this is a key issue in understanding the measurement uncertainty of the sampling system (rather than the measurement instrument uncertainty).

In addition, though the Rolls-Royce AIR6241 compliant system was constructed prior to the small engine testing, software control validation/debugging still needed to be completed. Thus unfortunately was not available for back-to-back testing on the small engine.

8.2 Small Engine Testing

The Gnome 1200 engine is an in-service Rolls-Royce single spool turbo shaft engine of late 1950’s design used on Wessex and Sea King helicopters. A two-stage turbine drives the 10 stage all-axial compressor, whilst a single stage free power turbine drives the load. The combustor is annular.

The engine experiments were performed using Jet A1 fuel. Engine conditions were varied from idle condition (low combustor pressure) through to cruise/climb conditions, by changing the throttle settings from 13,000 revolutions per minute (idle) to 22,000 rpm in 3,000 rpm steps. However, take-off (full power) was not achievable on the engine due to a volume limit of the exhaust extraction system.

Particle emissions from the Gnome have been previously characterised utilising size distribution analysis; from a DMS500[a]. Though these PM measurements were not obtained using an AIR6241 compliant sampling system, these size distributions help to establish the PM signature from the engine and indicate the growth in particle size from low to high engine power conditions as can be seen in Figure 98.

[a] Sevcenco, Y. A., Bowen, P. J., Johnson, M. P., Hilton, M., Welch, M. A. and Miller, M. N. “Mass and size distribution measurement of particulates from a gas turbine combustor using modern mobility analyzer and particle sizer”. 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit and 7th International Energy Conversion Engineering Conference, August 2009, Denver, Colorado, USA.

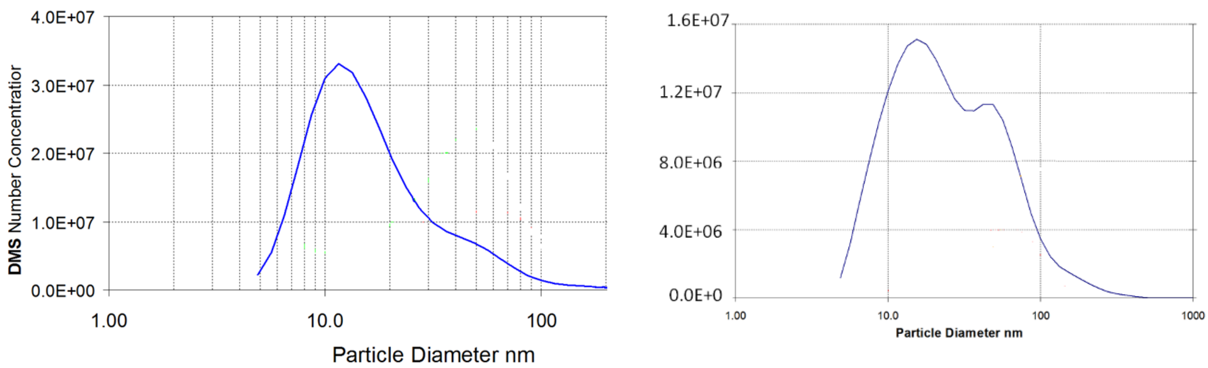


Figure 98 (a&b) DMS Total PM size distributions from Rolls Royce Gnome Engine for 13000rpm (left) and 22000rpm (right) power conditions

8.3 Experimental Setup

A single orifice probe (3/8" diameter) was located 1m downstream of a 90° bend in the engine exhaust duct and approximately 2m from the final turbine stage exit. Due to this duct length and bend, the exhaust emissions are expected to be well mixed. Thus the probe is likely to be representative of the engine exhaust.

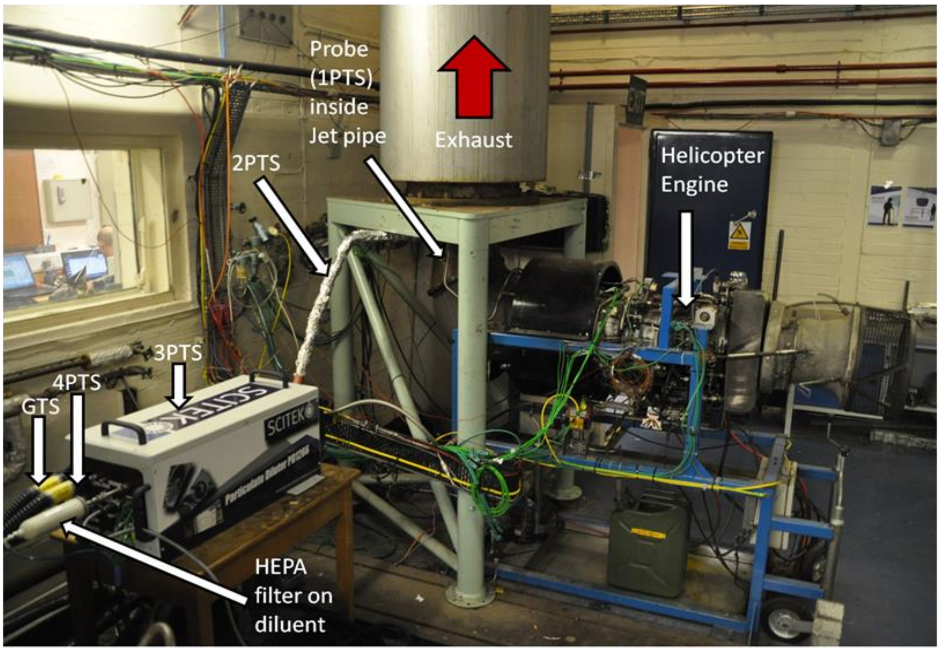


Figure 99 Gnome Engine Test Bed nvPM setup, Rolls Royce Derby,

The probe (1PTS) consisted of a 0.2m of 3/8" tube with a 90 degree bend facing into the exhaust flow. 2PTS consisted of an insulated heat traced 1.2m length of 3/8" tube.

Calibration gases and diluent (synthetic air) bottles were located outside the test cell as shown in Figure 100.

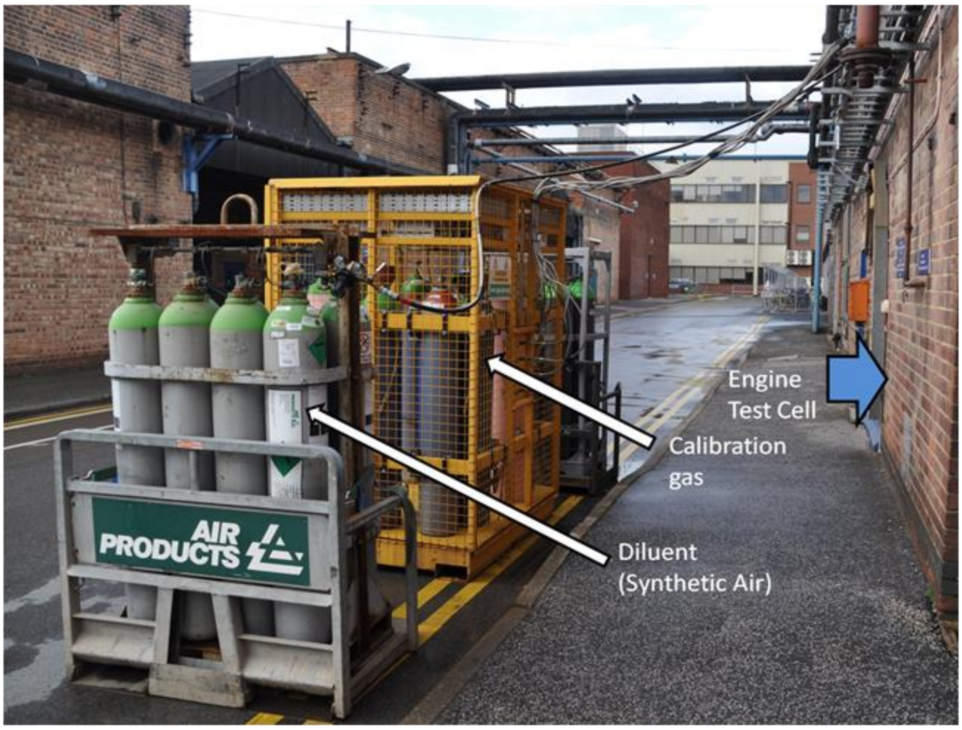


Figure 100 Setup of diluent and calibration gas bottles for Gnome engine testing

The specifications of the diluent zero and span gases are given below in Table 28.

Table 28 Diluent and calibration gas specifications

Description	Composition	Accuracy	Other	Expiry Date
Diluent (Synthetic Air)	20.9% O_2 (balance N_2)	±1% (<1ppm CO_2)	Air Products 2341300	26/08/2018
Zero Air	20.9% O_2 (balance N_2)	±1% (<1ppm CO_2)	Air Products 2604021	08/10/2018
Raw CO2 Span	4.99% (balance air)	±0.5%	Air Products 2605108	10/11/2019
1° Diluter CO_2 Span	0.5002% (balance air)	±1%	Air Products 2607356	12/09/2019

The EU/EASA reference system (5PTS & measurement instrumentation) was installed in the engine control room. The setup for the engine test can be seen below in Figure 101. Due to the confined space, the three racks were located behind each other instead of next to each other. This setup demonstrates the flexibility of the three rack system design. The details of the system are fully described in Section 6.3. However, the make-up flow and LII diaphragm pump were replaced with two rotary vane pumps (Model GAST 1532-701-RM012) with the intention to help prevent sample pressure fluctuations affecting the MSS measurement (solved for the Zurich testing by including semi-infinite tubing as a buffer volume). The pump type change was successful in meeting this objective and the semi-infinite tube was not required.

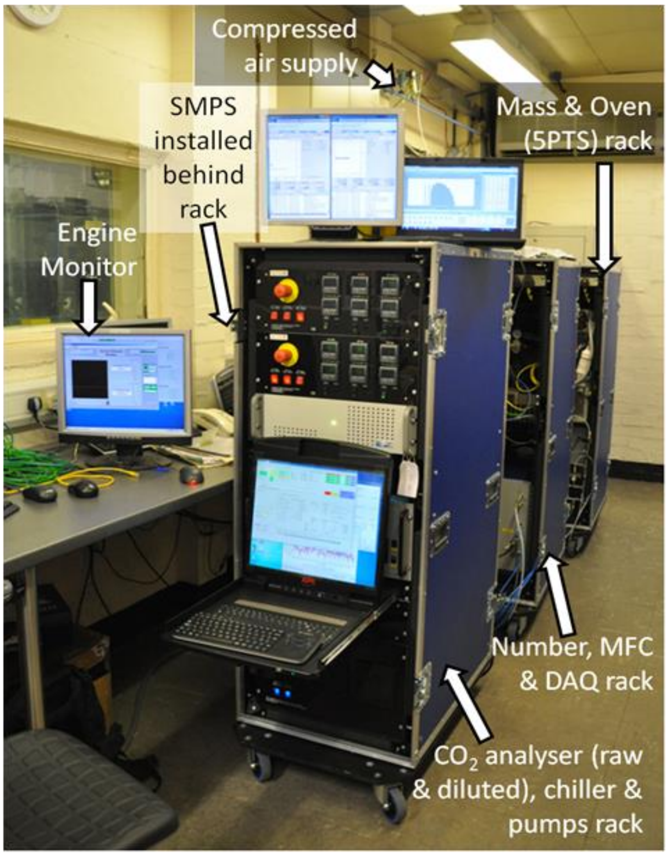


Figure 101 EU/EASA reference system installation for Gnome engine test

For additional nvPM characterisation, a SMPS was used to obtain non-volatile particle size distributions downstream of the APC (VPR/CPC).

The SMPS was a TSI model 3936 base unit with a 3776 particle counter. The base unit was configured with a nano-DMA, model number 3085. The 3776 has a quoted D_{50} of 2.5nm and was within 1 year of its last calibration. The 3085 DMA had been serviced approximately 2 years ago, but had been unused and in storage since then. The 3085 was also calibrated using NIST traceable PSL spheres as part of the testing, as per the manufacturer instructions, and all data reported has been corrected for the specific configuration of sample pipe lengths used. For all tests, the SMPS was operated with a sheath flow of 3 l/min and the 3776 was operated in low flow mode, 0.3 l/min. A total scan time of 2 minutes was selected and this, in combination with the sheath flow, gave a measurable diameter range of ~4.5 to 160nm.

Throughout the tests, a TSI virtual impactor was used on the SMPS inlet to a) allow a precise measure of the aerosol flow to be made and b) to remove the influence of large particles which can affect the inversion algorithms. Details of both can be found in the TSI manuals.

The SMPS sampled on the excess flow of the APC to prevent the APC experiencing a back pressure caused by the SMPS, a flow splitter was used to take sample and exhaust the excess flow. The splitter was a 3 way splitter manufactured by the University of Manchester. The splitter had one port sampling along the centre line and two at approximately 30 degree angles from the centre line. The SMPS sampled from the straight through port to minimise any potential losses, which are assumed to be minimal.

It is important to understand how the 3776 achieves the lower cut of 2.5nm and the effect this has on the counting statistics. The counter works by growing nanometer particles by condensation of butanol in a supersaturated environment to a size that can be detected optically. To count the very smallest sizes, the counter confines the aerosol stream to the centre of the condensing region by use of a sheath air flow. The sheath air flow is generated by sub-sampling the inlet flow and filtering it for all particles. In low flow mode, the inlet samples at 0.3 l/min, of which 0.25 l/min are used for sheath flow. Therefore, only 0.05 l/min (or 16.7%) of the inlet flow is counted. This has an impact on the counting statistics, and is the trade off for detecting small particles.

The counter is not the only influencing factor on the counting statistics. The SMPS works by sampling charged particles. The method of charging, using a radioactive source, does not charge all particles and the inversions have to multiply up the data to correct for this. For example, at 29nm (GMD of the 19,000 RPM tests), the fraction of particles carrying one charge is only ~15%. The actual number detected by the SMPS (i.e. without dilution correction applied) was approximately 180 /cc at 29nm for the same tests. Assuming the 15% efficiency, this is a total of 27 /cc. The SMPS sampled ~100 channels in 120 seconds, or 1.2 seconds per channel. With a flow of 0.05 l/min going through the detector, this gives the total volume sampled of 0.05 * 1000/60 (l/min to cc) * 1.2 = 1 cc. Therefore the total number of particles counted in that size bin is approximately 27*1 = 27. The low counting statistics coupled with the large corrections (both instrumental and dilution) yields very noisy data.

This noisy data is observed in the size distributions (average of 3) obtained on the range of engine power conditions in Figure 104.

Therefore to increase the counting statistics for the SMPS and therefore increase confidence in the size distribution data, the VPR dilution setting was set at the minimum (PCRF 100, DF2 63:1). The dilution sensitivity analysis was performed with these settings. In addition, to obtain statistical relevance, 7 x SMPS scans were performed at each experimental condition.

8.4 Results

In addition to performing nvPM engine measurements, cleanliness and ambient measurements were also performed in compliance with AIR6241. In addition, as per ARP1256 gas analysers were calibrated once an hour during engine testing.

8.4.1 Emission Indices Results

Conventional gaseous and smoke emissions for this engine were obtained previously using ARP1256 and ARP1179 methodology at two of the engine conditions (same probe location used). The data obtained is shown below in Table 29. Together with the nvPM EI data (for these two engine conditions only) obtained with AIR6241 methodology.

Table 29 EI Gaseous and PM results for Rolls Royce Gnome Engine

Engine Condition (rpm)	CO2 (%)	EI CO (g/kg)	EI HC (g/kg)	EI NOx (g/kg)	Smoke Number	EI mass (mg/kg)	EI number (#/kg)
13000	2.31	139	70.2	0.61	3.2	18.5	1.6 e15
21000	1.89	56.5	21.0	2.31	6.8	80.5	3.0 e15

The nvPM EI mass data (for both LII and MSS) across the engine power range is shown below in Figure 102. It can be observed that the highest EI mass occurs at the highest power condition. The lowest EI mass occurs at an engine power just above GI (10000 rpm), with a slight increase in EI mass at GI. Note that all the raw mass measurements were above 3xLOD (unlike some of the measurements in Task 3). As observed in Task 3 with the Zurich testing, the MSS reads higher than the LII at around 20% across the engine conditions.

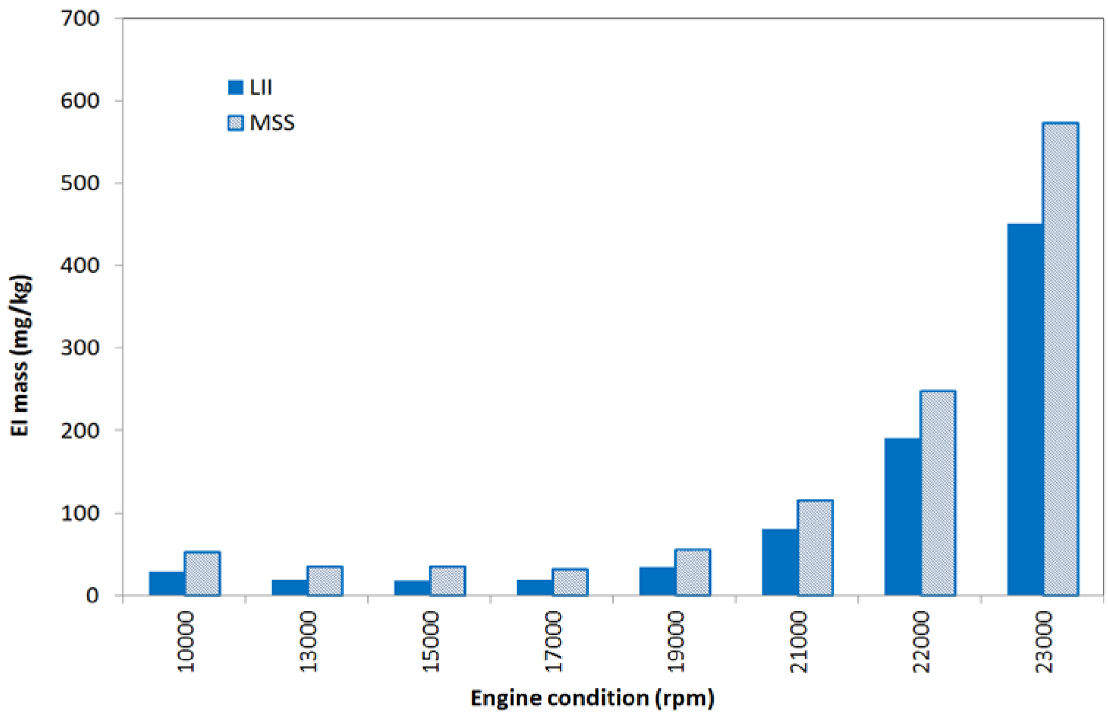


Figure 102 Emission Index nvPM Mass measurements (using LII and MSS) from Gnome engine, using single probe

The nvPM EI number data across the engine power range is shown below in Figure 103. It can be observed that the highest EI number occurs at the highest power condition. The lowest EI mass occurs at a low-to-mid range engine power, significant increase in EI number at GI. Note that all the raw number measurements were obtained in the AIR6241 traceable CPC calibration range.

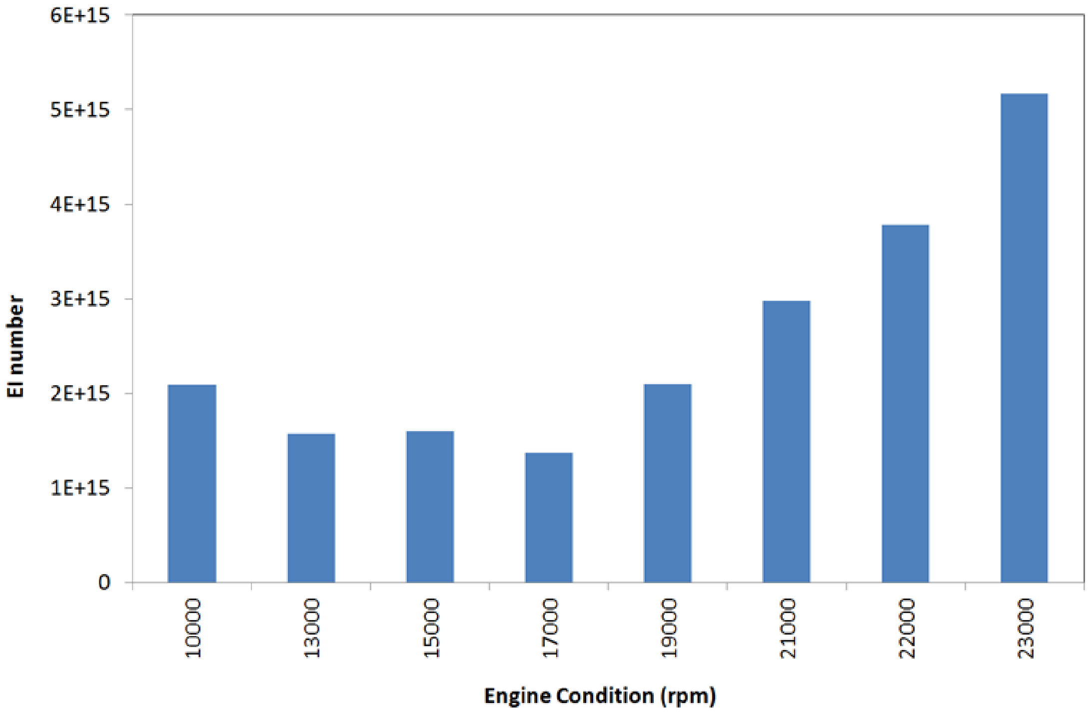


Figure 103 Emission Index nvPM Number measurements from Gnome engine, using single probe

Non-volatile PM size distributions (corrected for dilution) for each engine power condition are shown below in Figure 104. Even though the data is noisy (as explained in 8.3) the lognormal curve fits agree with the mass and number measured data (highest PM signature at high powers and lowest PM signature at a low power but not the lowest), and show the difference in particle size across the engine range.

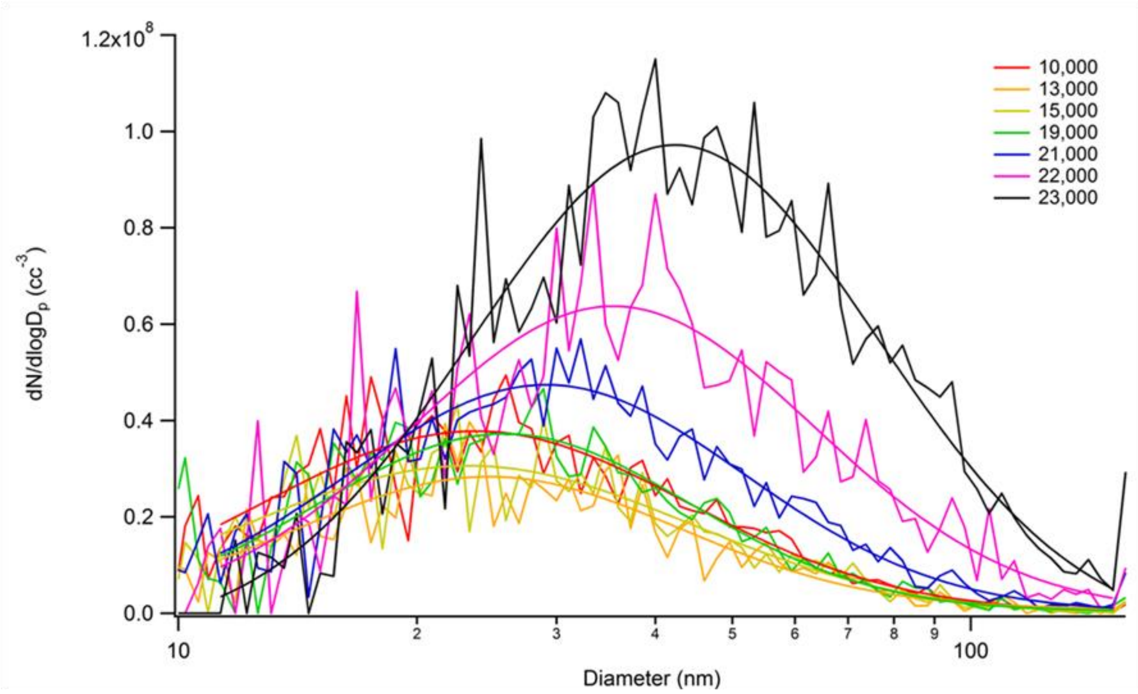


Figure 104 SMPS nvPM number size distributions (dilution corrected, average of 3 distributions) with lognormal curve fits from Gnome engine, using single probe

The geometric mean diameters (size distribution peak) for each engine power are shown below in Figure 105. The shift to larger size particles at high engine powers is clearly seen.

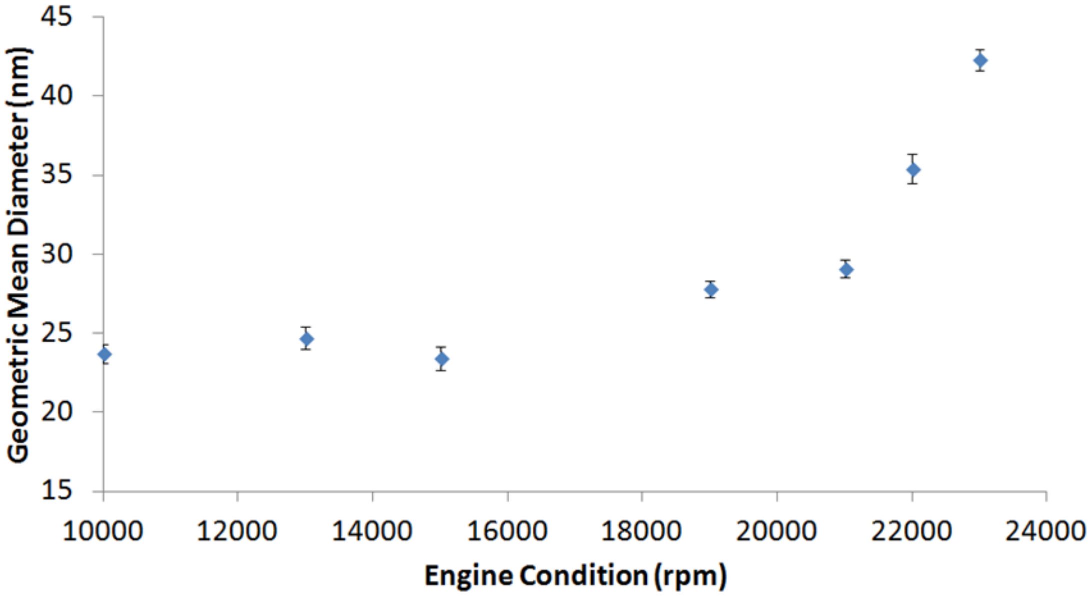


Figure 105 Geometric mean diameters for the gnome engine, using single probe

To help with the ICAO nvPM certification process, this data can be used by CAEP WG3 PMTG as part of the 'Small' engine database

8.4.2 Dilution Factor Sensitivity

Sensitivity of particle concentration to primary dilution factor for an AIR6241 system was observed during SAMPLEIII SC02 (engine CFM56-5B4-2P) with a number of explanations suggested. However, as the observations were not conclusive, a specific experiment was carried out in Task 3b and as described above, no impact of dilution sensitivity was seen. However, the PM number and mass concentrations for the CFM56-7B26/3 were lower than measured from CFM56-5B4-2P and it was hypothesised that if coagulation was the basis for the DF1 sensitivity then the experiment would need to be repeated on an engine source with a higher nvPM concentration.

To provide a further dataset on dilution sensitivity on nvPM mass as well as number, the primary dilution factor (DF1) was varied (using the diluent inlet pressure). This is a repeat of the experiment carried out in Task3b but with a different engine signature and different probe (1PTS) and 2PTS sampling system (1PTS & 2PTS described in section 8.3).

Based upon the nvPM data obtained during the detailed engine power curve, two engine conditions with different nvPM signatures were chosen to study, and where possible DF1 was varied as far as possible. The dilution corrected number concentration at the 19000 rpm condition were approximately double that of the highest particle number concentration observed on the CFM56-7B26/3, with the 23000 rpm approximately twice as high again.

Prior to altering DF1, data was obtained to indicate whether DF2 (VPR dilution) was having any affect. Data was obtained at a variety of DF2 (PCRF) settings. The dilution corrected size distributions are shown below in Figure 106. It can be observed that though the concentration changes slightly, it is within measurement uncertainty and there is no impact on the peak size (GMD).

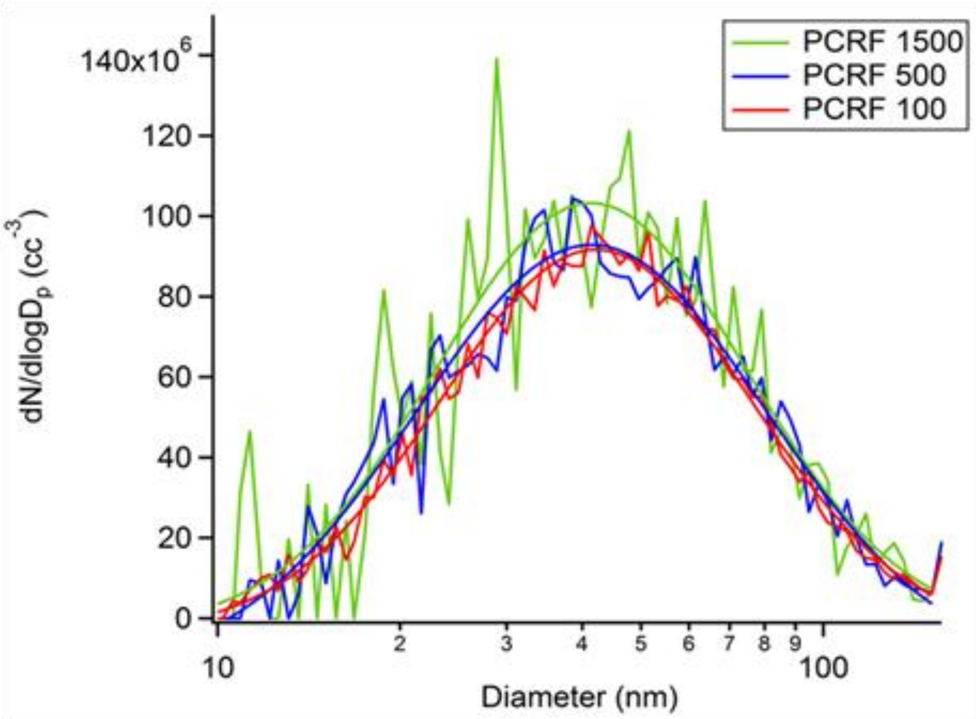


Figure 106 SMPS nvPM number size distributions (corrected for dilution) at various DF2 (PCRF setting) factors at 23000 rpm Gnome engine setting (average of 3 distributions)

Data was then obtained at engine condition of 23000 rpm for a variety (by altering the diluent pressure) of Dilution Factors (DF1) and is presented below in Figure 107. For this data set, unlike the CFM56-7B26/3 dataset, the number size distribution analysis clearly shows the coagulation mechanism (high particle concentrations reduce in number and grow with a low DF1/Primary Dilution). Note that though two of the DF1 are slightly outside the AIR6241 prescribed range, particle growth and number concentration reduction does occur within the current DF1 specifications.

The same data is plotted in Figure 108 as nvPM mass size distributions. The data is consistent with Figure 107 in that the coagulation mechanism has only a very small impact on mass concentration (larger particles have better diffusion penetration), and this is what is observed here.

The Geometric Mean diameters (peak location) are plotted in Figure 109 and provide further evidence of coagulation. High Dilution Factor = Smaller size particles.

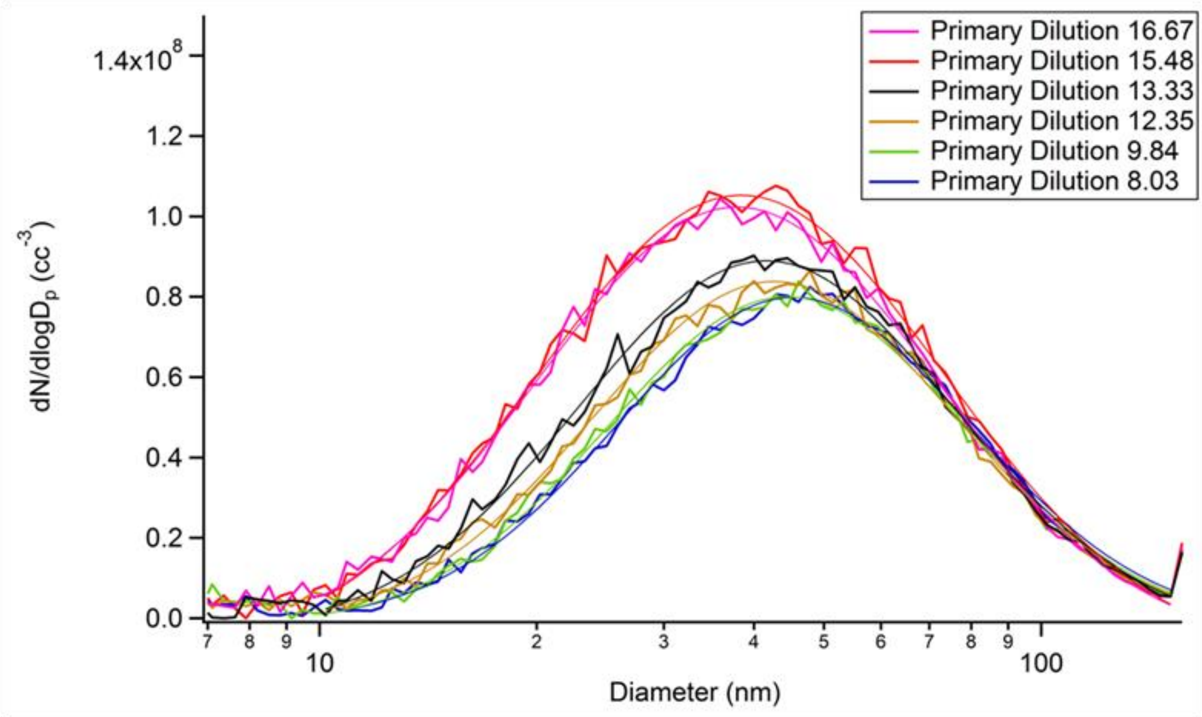


Figure 107 SMPS nvPM number size distributions (average of 7) over a range of DF1 (Primary Dilution) at 23000 rpm Gnome engine setting

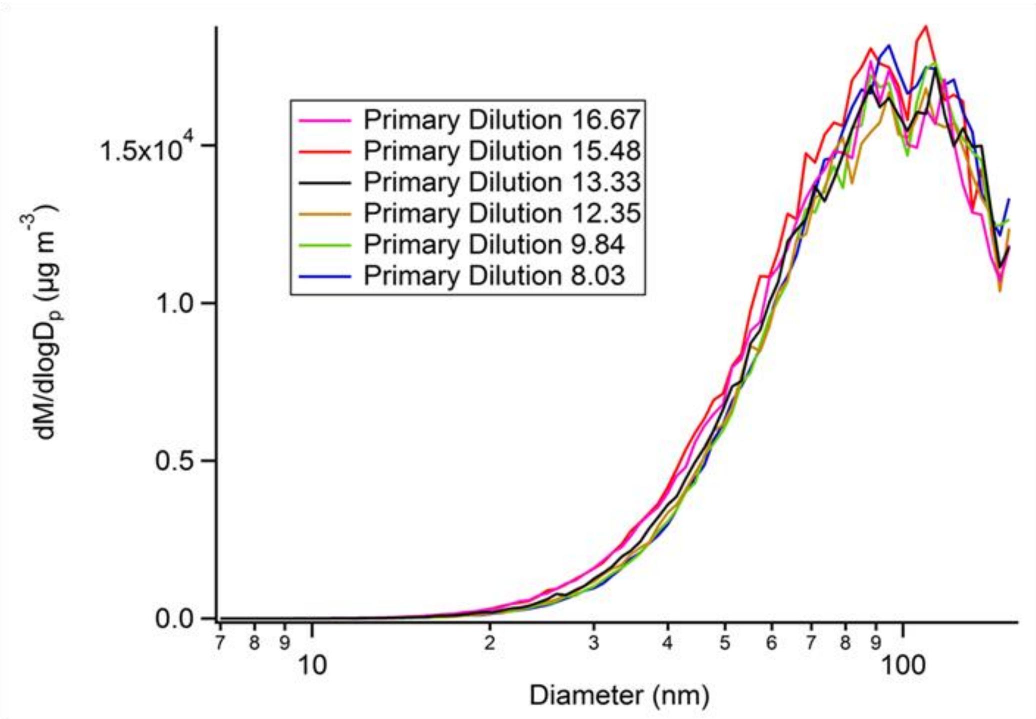


Figure 108 SMPS nvPM mass size distributions (average of 7) over a range of DF1 (Primary Dilution) at 23000 rpm Gnome engine setting

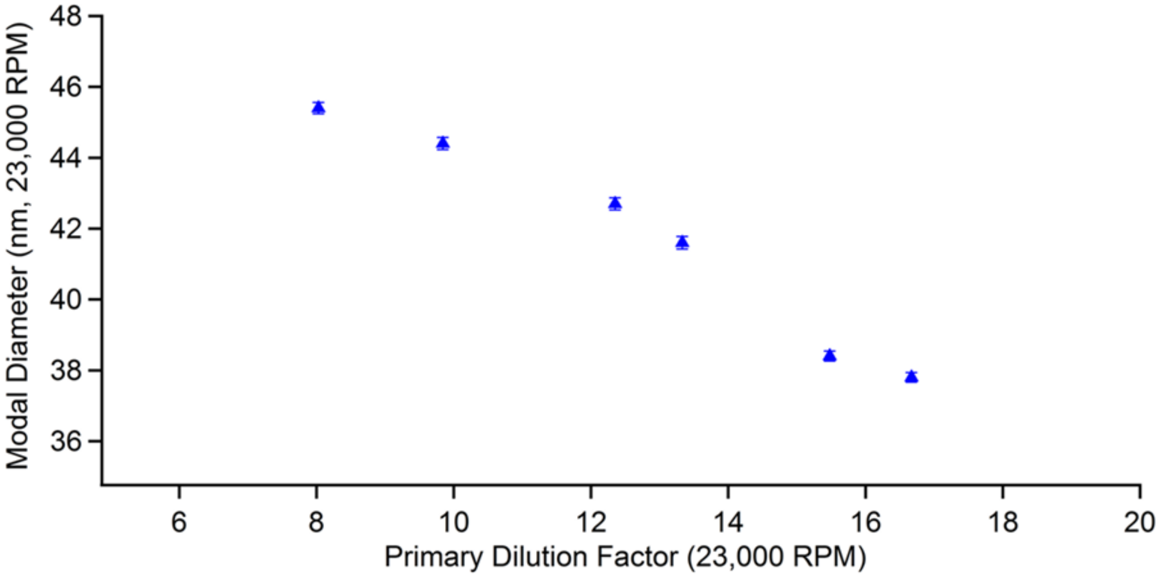


Figure 109 Graph showing dilution factor sensitivity for GMD for the Gnome engine at 23000 rpm

The same types of graphs were produced for 19000 rpm engine condition. The graphs illustrate the lower mass and number concentrations witnessed for the 23000 rpm condition. The curves tend to shift to smaller diameters at a lower DF1 which would be consistent with coagulation in Figure 110. However, it is not as clear as for the higher power/higher PM concentration condition. Note that even by altering the diluent pressure it was not possible to reduce DF1 further than 12.1.

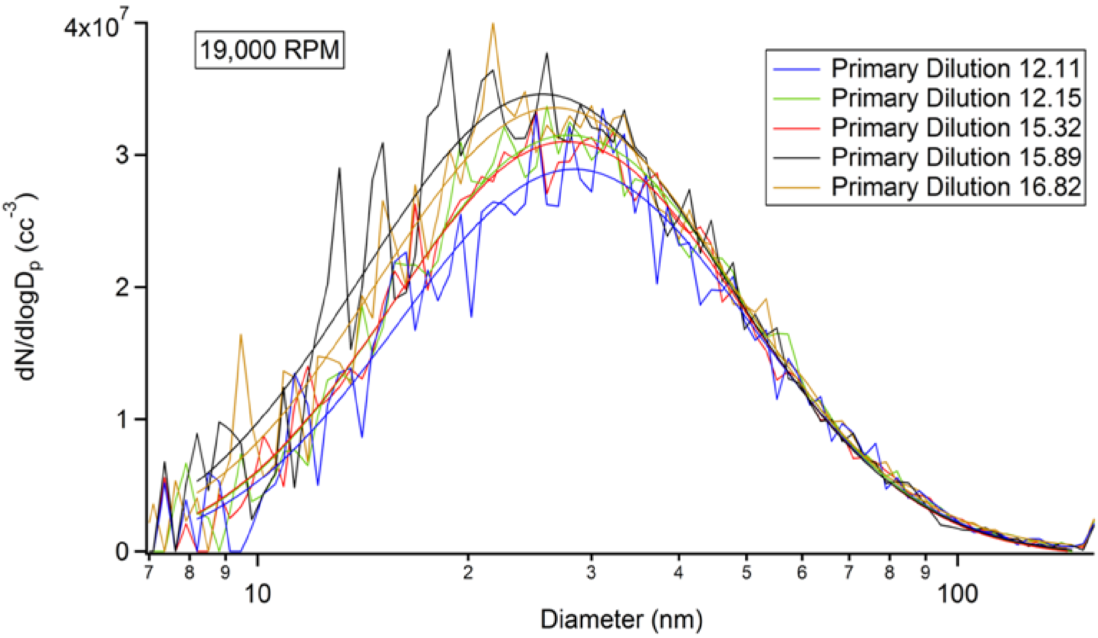


Figure 110 SMPS nvPM number size distributions (average of 7) over a range of DF1 (Primary Dilution) at 19000 rpm Gnome engine setting

The nvPM mass size distributions again show no impact of dilution factor sensitivity in Figure 111.

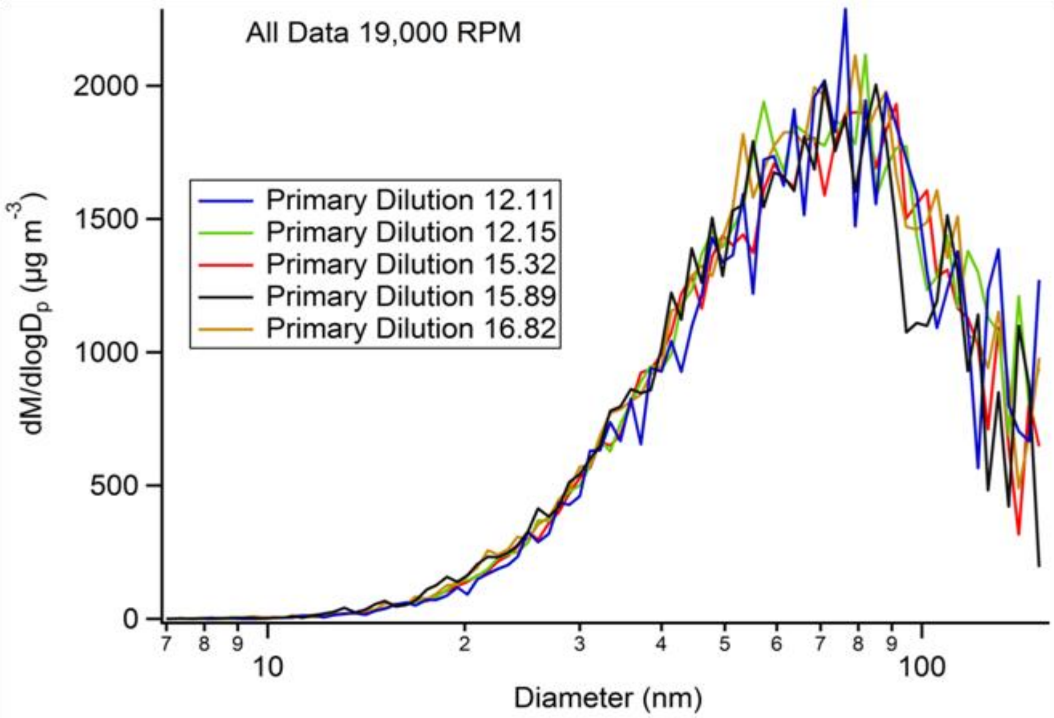


Figure 111 SMPS nvPM mass size distributions (average of 7) over a range of DF1 (Primary Dilution) at 19000 rpm Gnome engine setting

When comparing GMD at 19000 rpm engine conditions in Figure 112, the dataset is again not straight forward. However, the 19000 rpm data was obtained over a small range of different ambient temperature conditions (18.5 to 21°C) which may account for some of the variability observed.

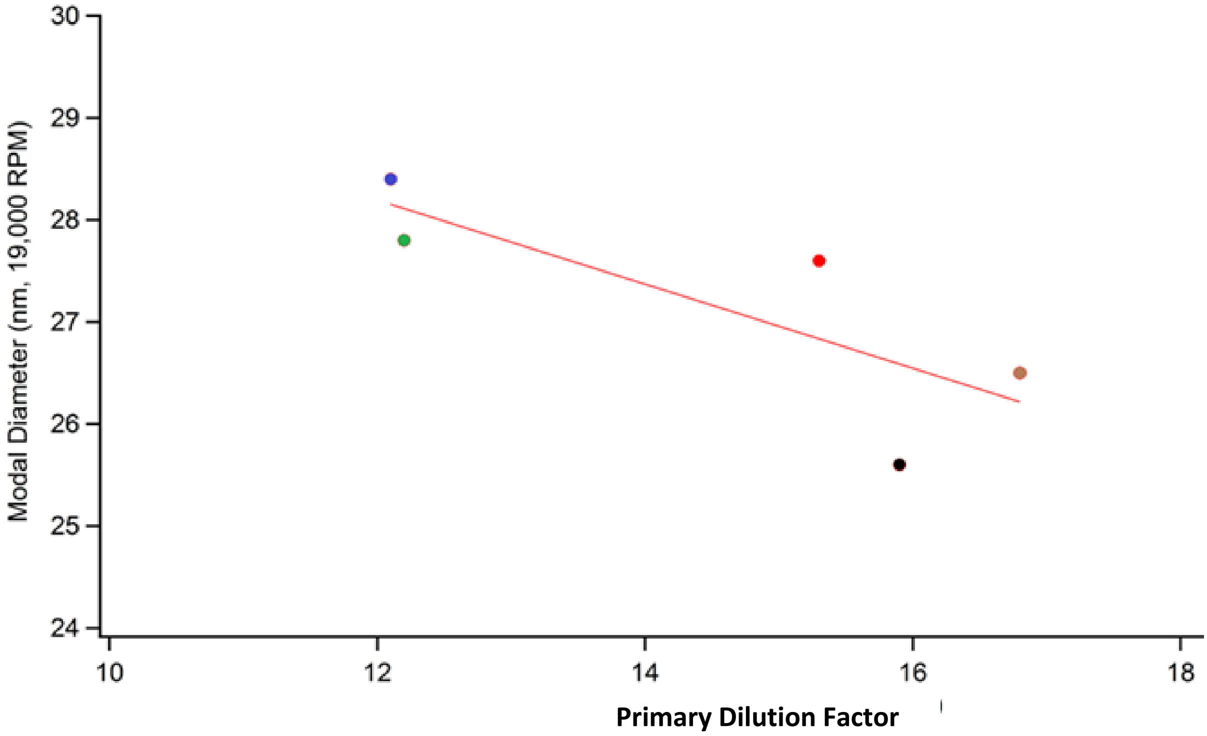


Figure 112 Geometric mean diameters over a range of dilution factors (12.1 to 16.8) at a stable engine condition (19000 rpm) – (mixture of 3 runs at different ambient temp), Run 1 (18.5°C): red, Run 2 (20°C): green, brown, Run 3 (21°C): blue & black

To consider the dilution sensitivity impact on EI number and mass at 23000 rpm engine condition, the EI data can be plotted using both the integrated size distribution data, (Particle sphericity and unit density are assumed for mass) and the AIR6241 instrumentation. For the LII measurement the analyser was operating within compliant limits. However, as explained above, the VPR DF (DF2) was kept low (63 DF) to ensure that the size distribution measurements were as accurate as possible. Thus the CPC measured number concentrations were above the limit for single count mode (with 10% coincidence). Therefore analysis of this data set can only be used to indicate qualitative trends rather than quantitative concentration.

Figure 113 shows that depending on the DF1 setting used, the data indicates that the EI number could be up to a factor of 2 different to another DF2 setting (within AIR6241 specifications). Note the CPC is outside the traceable calibrated range. It is simultaneously observed that the EI mass, though variable, is within expected measurement tolerances and does not show a clear trend (in accordance with the number and mass size distributions shown above).

Figure 114 Dilution Factor impact on EI mass and number (calculated from size distribution) for 23000 rpm on Gnome engineFigure 114 shows the EI data calculated from the size distributions across the DF1 range. The same dilution sensitivity findings are observed as in Figure 113. Though it should be noted that the SMPS is indicating a significantly higher EI number, it is unknown whether this is due to the CPC being outside the traceable range or the number of assumptions used in the SMPS methodology. The SMPS is indicating a slightly higher EI mass and this possibly due to the assumptions of sphericity and effective density.

The dilution corrected number concentrations (SMPS) for the 23000 rpm engine condition range from 5.0E7 to 7.5E7 #/cm^3.

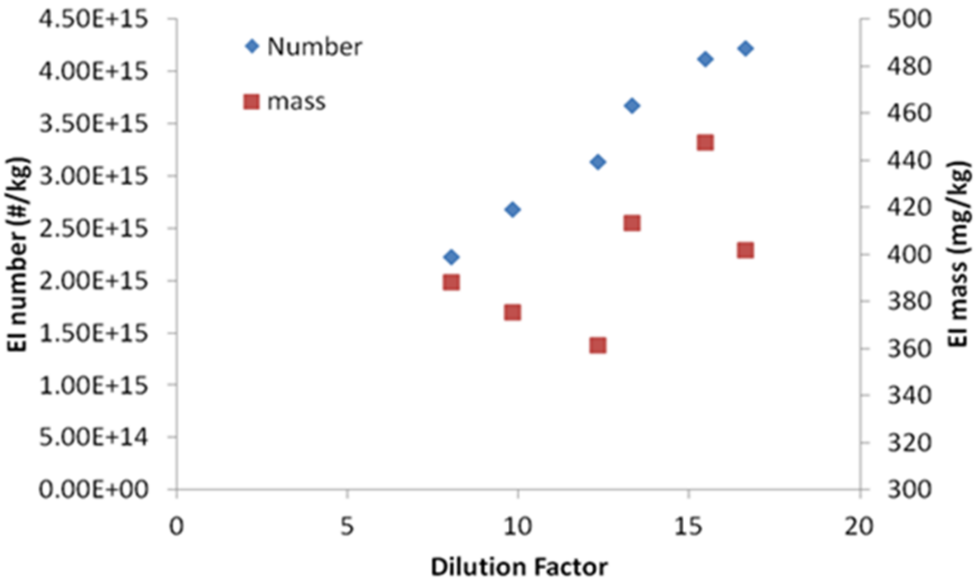


Figure 113 Dilution Factor impact on EI mass and number (calculated from LII and CPC) for 23000 rpm on Gnome engine

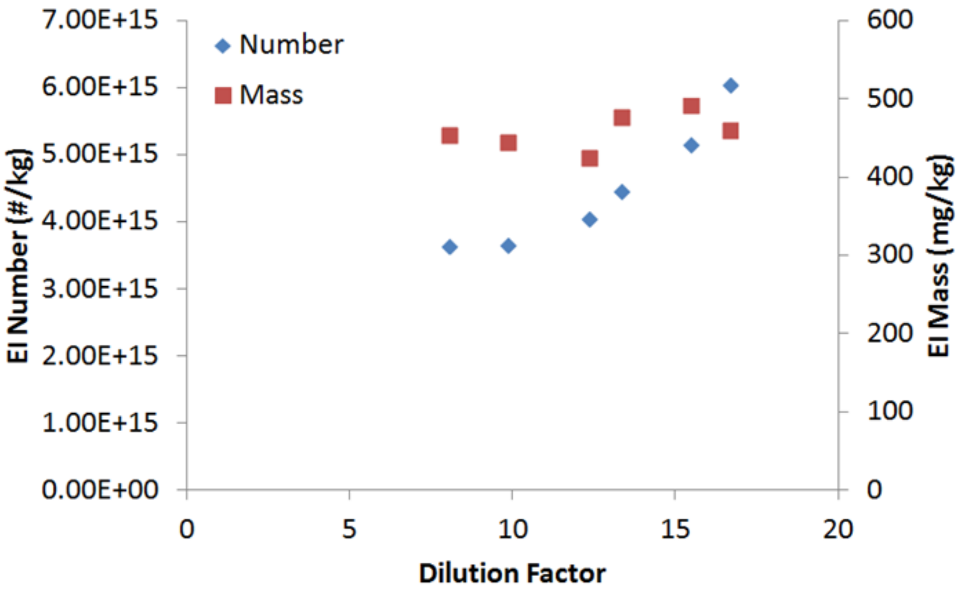


Figure 114 Dilution Factor impact on EI mass and number (calculated from size distribution) for 23000 rpm on Gnome engine

The same dilution sensitivity/Emission Index impact graphs are shown below (Figure 115 and Figure 116) for the 19000 pm engine condition. As shown by the size distributions, the trend that coagulation might be taking place is not strong. There is no trend for mass, though for number there does seem to be a small trend towards higher concentrations at higher dilution factors. The same trends are observed in both the CPC/LII and SMPS data. Though for this lower particle concentration engine condition the SMPS total number concentration is slightly lower than the CPC and again a higher mass concentration than the LII.

The dilution corrected number concentrations (SMPS) for the 19000 rpm engine condition range from 1.9E7 to 2.3E7 #/cm^3.

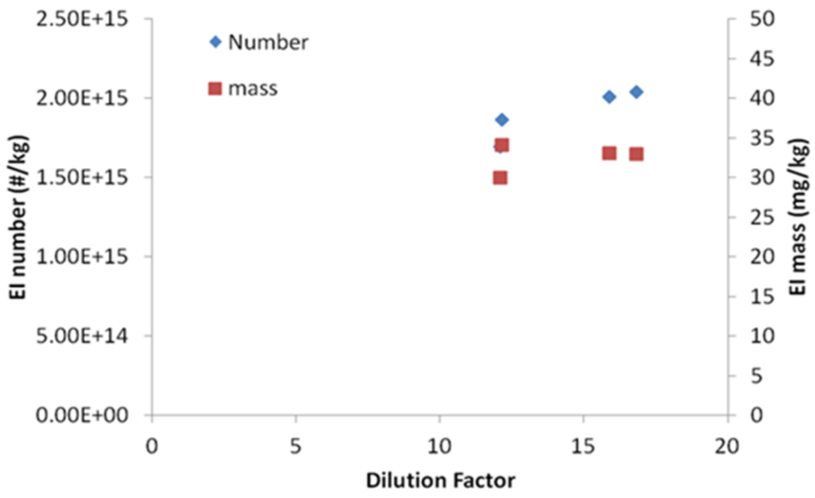


Figure 115 Dilution Factor impact on EI mass and number (calculated from LII and CPC) for 19000 rpm on Gnome engine

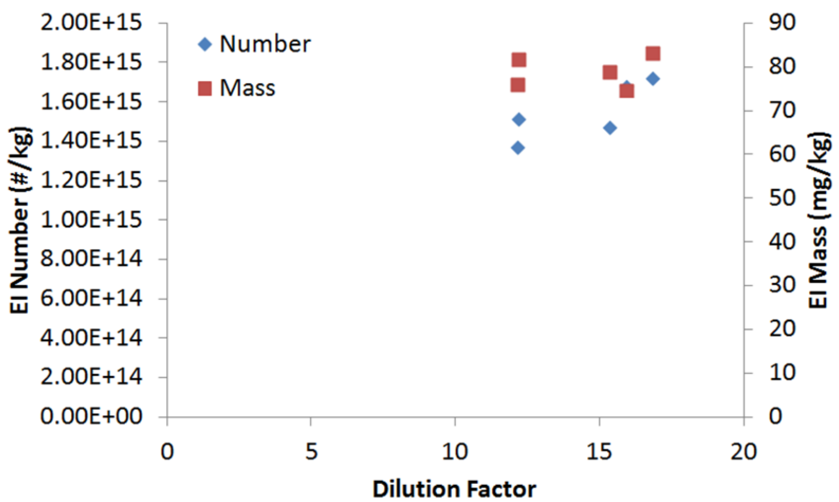


Figure 116 Dilution Factor impact on EI mass and number (calculated from size distribution) for 19000 rpm on Gnome engine

The results from this dilution factor sensitivity study indicate that coagulation is occurring for the Gnome engine nvPM measurement. Theory dictates[a] that the impact of coagulation on number concentration is negligible for <1E7 #/cm^3, but at higher inlet concentrations the reduction in measured concentration can be significant. These theoretical numbers correlate

[a] Giechaskiel, B., et al., "Sampling of Non-Volatile Vehicle Exhaust Particles: A Simplified Guide," *SAE Int. J. Engines* 5(2):379-399, 2012

with the observations both on the CFM56-7B26/3 (raw number concentrations <1E7 #/cm^3) and the Gnome (raw number concentrations >2E7 #/cm^3).

The Gnome engine has a low efficiency legacy combustor, but it is unknown where the coagulation threshold margin lies across legacy/modern combustor type technology. And therefore there could be an impact on how to calculate a particle line loss correction.

8.5 Conclusions

1. During the engine testing it was generally possible to meet DF1 range specifications for the small thrust engine (with the single point probe). However, it was observed that at the lowest engine thrust the DF1 increased to 13.2 (just outside the specified 8 to 13 range). As such the authors make the following recommendations:
   - DF1 diluent pressure is added to AIR6241 methodology (noting that it should be proven for a specific diluter, what is the lowest workable diluent pressure with 25 slpm being drawn from the diluter exit without sucking in ambient air through the vent)
   - Assess increasing AIR6241 compliant DF1 range to 8 to 14, noting that as more engine manufacturer's engines and probe/rake designs are tested, the range may need to be extended further prior to the finalised ARP.
2. DF1 nvPM number sensitivity was clearly observed (statistically significant for the AIR6241 specified range) at the higher power conditions. The size distribution analysis suggests that coagulation was occurring. Though the Gnome engine has a legacy-type combustor it is unknown where the coagulation threshold margin lies across legacy/ modern/ development combustor type technology.
3. More investigation and datasets are required to assess the impact on the measured particle number concentration and future line loss correction uncertainties, accounting for possible coagulation. Therefore the authors recommend:
   - During future engine PM testing (single or multiple measurement system), PM data is obtained at different DF1 (by altering diluent pressure) at a steady state condition across a range of engine powers. If possible at the highest DF1 achievable with the system.
   - the impact of coagulation is considered for possible future sampling system line loss correction
4. The extent of coagulation in the first section of sampling line between probe inlet and diluter inlet is unknown, for all the engines tested. At the lower engine power conditions (lower number concentrations) data from R-R Gnome test seems to confirm if probe inlet number concentrations are greater than ~3x10^7 #/cm^3 coagulation is likely in that section of line (dependent on residence time in 1PTS/2PTS sections).
5. Changing the make-up and LII pump from a diaphragm type to rotary type removed the AVL MSS noise interference without having to install a buffer volume between the pump and instrumentation.
6. nvPM emissions data was obtained on a small turbo shaft helicopter engine Rolls-Royce Gnome. Again a similar trend was observed with the maximum EI mass (~450 mg/kg) and largest particle sizes (~43 nm) observed at the highest engine conditions. The maximum EI number (~5E15 #/kg) was also observed at the highest engine power. Noting that the true maximum EI number would be higher due to the observed coagulation effect. Both the lowest EI mass (~18 mg/kg) and EI number (~1.4E15)

#/kg) were observed at low engine power conditions above ground idle and had the smallest particle sizes (~24 nm). The EInumber and EImass increased slightly at ground idle conditions. As in line with AIR6241, these EI's are not corrected for particle loss in the system.

9. Conclusions

A summary of all of the conclusions made in Tasks1-4 is presented below:

1. The SAE E31 nvPM AIR 6241 was prepared in time for a ballot prior to the SAE E31 2013 annual meeting
2. AIR6241 was successfully balloted by SAE E31 after technical and editorial comments implemented
3. The SAE E31 nvPM ARP is currently on schedule for end of 2014. The ARP's delivery will depend upon proof of robust measurement and operational testing of the proposed nvPM system by engine manufacturers.
4. Data from SAMPLEIII SC02, suggests a repeatability of 20% or better for nvPM mass and 30-40% for nvPM number if considering repeats on a particular engine.
5. Thrust levels can be used to consider total nvPM variability on repeated engine data, however, it is likely that engine manufacturer proprietary parameters (such as T30) will need to be plotted to fully assess nvPM engine variability.
6. Analysis of existing data indicates that it is not obvious, due to conflicting combustion physical processes (related to combustor inlet Temperature and Pressure), whether ambient corrections are required for nvPM. There is some limited evidence that elevated ambient temperature may reduce PM.
7. Engine-to-engine variability data may or may not encompass variations in ambient conditions
8. Combustion rig testing (with AIR6241 instrumentation) is likely required to consider the effects of Fuel-Air-Ratio (FAR) and P30 (inlet combustor pressure) independently
9. Consideration of variability expectations for engine-to-engine need to be considered by regulators and funding bodies, in order that regulated values including statistical compliance can be adopted.
10. More engine testing is required with AIR6241 sampling/measurement systems to assess engine-to-engine variability.
11. An EU/EASA mobile reference system was constructed in compliance with both AIR6241 and SAE E31 recommendations for a non-volatile PM reference system
12. Three AIR6241 compliant systems, 2 mobile (EU/EASA and North American) and 1 fixed (Swiss) were successfully inter-compared (to be known as 'reference' systems) on a CFM56-7B26/3 engine PM source.
13. Long term inter-comparability of compliant reference systems is needed.
14. AIR6241 Primary Dilution Factor (DF1) range limits were met for the EU/EASA system across all CFM56-7B26/3 engine conditions during the Zurich testing. This was achieved by controlling the diluent pressure and spill valve position upstream of Diluter 1.
15. It was not always possible with the EU/EASA reference system to keep the GTS flow rates within existing Annex 16 specifications, whilst ensuring DF1 was in AIR 6241 specification. This was particularly observed at low engine power, thus simultaneous

gas, smoke and nvPM measurements would not be possible with the Zurich probe geometry tested.

16. Discrepancies were observed in the three reference systems for DF1 during the multiple system testing. Typically the Swiss system was significantly lower than the EU/EASA system and the North American system slightly higher (sometimes outside the AIR6241 specified range). However the effect of simultaneous sampling of multiple systems will have had an effect on DF1 compared to what may be achieved during single system testing.
17. During the small engine testing in Derby it was generally possible to meet DF1 range specifications for the small thrust engine (with the single point probe). However, it was observed that at the lowest engine thrust the DF1 increased to 13.2 (just outside the specified 8 to 13 range). As such the authors make the following recommendations:
    - DF1 diluent pressure is added to AIR6241 methodology (noting that it should be proven for a specific diluter, what is the lowest workable diluent pressure with 25 slpm being drawn from the diluter exit without sucking in ambient air through the vent)
    - Assess increasing AIR6241 compliant DF1 range to 8 to 14, noting that as more engine manufacturer's engines and probe/rake designs are tested, the range may need to be extended further prior to the finalised ARP.
18. During the AIR6241 system cleanliness (and leak) checks the mass instruments met specification; however, the number specification was unable to be met (on both the EU/EASA and North American systems). It was proven that the rotary diluter seals of the AVL APC were the leak source, the cause being the lower APC inlet sample pressure witnessed on both the EU/EASA and North American system compared to the Swiss system.
    - Recommend that the AIR6241 zero limit be increased at least as a minimum from 0.5 to 1 particles/cm^3 (for the lowest DF2 used for the measurement), noting that at even at 5 particles/cm^3 the additional uncertainty would only be 0.25% when compared to the AIR6241 existing traceable CPC calibration range.
19. Ambient mass and number data was obtained as per AIR6241 specifications. However, there is inconsistency in the length of time required by AIR6241 for ambient (and zero) measurements (3 minutes) compared to engine measurements (30s)
20. During the VPR performance check, it was observed that there was a small impact of inlet sample pressure on the measured Dilution Factor (DF). The instrument dilution settings were only just within the AIR6241 10% limits. At this time it is unknown why the DF measured during the performance check were different to those quoted during the calibration certification. As such the authors recommend that:
    - The VPR performance check is conducted at a sample inlet pressure condition representative of system operation.
    - During future system measurements, the VPR DF check is monitored over time to check for long term drift.
21. It was observed that PM data took numerous minutes to stabilise, (typically ~2 to 4 minutes) after the engine reached a new power condition. The judgement for stable emissions conditions has historically always been performed by visual assessment of real time gaseous data. However, an expression using 2 standard deviations is

proposed as a possible candidate for verifying w a data-point stable. The authors thus recommend.

- SAE E31 should consider whether visual observation or a mathematical expression should be used to verify PM stability.

22. Large spikes in mass concentration were observed at the maximum continuous engine condition, on the 'multi-point' cruciform probe. These spikes were attributed to 'particle shedding' (similar to observations in SAMPLE I rig measurements) from the internal probe surfaces.
23. It was observed that the nvPM number concentration could vary during the evaporation tube/ CS heating cycle. Therefore the authors recommend
    - Pre-heating the evaporation tube / catalytic stripper to at least 360°C for several hours after receiving the instrument back from calibration, before cooling back to 350°C.
24. No impact of DF1 sensitivity was observed on the CFM56-7B26/3 engine over a range of engine power conditions. However, DF1 nvPM number sensitivity was clearly observed (statistically significant for the AIR6241 specified range) on the small helicopter engine at the higher power conditions. The size distribution analysis suggests that coagulation was occurring. Though the Gnome engine has a legacy-type combustor it is unknown where the coagulation threshold margin lies across legacy/ modern/ development combustor type technology.
25. More investigation and datasets are required to assess the impact on the measured particle number concentration and future line loss correction uncertainties, accounting for possible coagulation. Therefore the authors recommend:
    - During future engine PM testing (single or multiple measurement system), PM data is obtained at different DF1 (by altering diluent pressure) at a steady state condition across a range of engine powers. If possible at the highest DF1 achievable with the system.
    - the impact of coagulation is considered for possible future sampling system line loss correction
26. The extent of coagulation in the first section of sampling line between probe inlet and diluter inlet is unknown, for all the engines tested. At the lower engine power conditions (lower number concentrations) data from R-R Gnome test seems to confirm if probe inlet number concentrations are greater than $\sim 3x10^7$ $\#/cm^3$ coagulation is likely in that section of line (dependent on residence time in 1PTS/2PTS sections).
27. Neither the nvPM mass or number concentrations were statistically sensitive to DF1 diluent composition (Synthetic Air or Nitrogen)
28. Successful online DF2 measurements via CO_2 were performed. No significant differences were observed between online DF2 and pre-test DF2 check values (variance was within AIR6241 10% allowance specification for the VPR DF check). The authors note that the online methodology could be improved if the CO_2 analyser and calibration gas specifications were improved beyond ARP1256 requirements.
29. The 3 reference PM number instruments were sent to the instrument manufacturer for calibration in accordance to AIR6241 specifications, as a result instrument penetration limits needed to be reduced by the SAE E31 prior to the final document ballot, in order to meet conformance.
30. During the reference nvPM instruments annual calibrations, several calibration issues were encountered at the (ISO 17025 compliant) qualified calibration laboratory. As

such the only VPR/CPC in full AIR6241 compliance was the North American system. Therefore the authors recommend:

- VPR/CPC suppliers develop a specific aviation specification calibration certificate. This should include close liaison with SAE E31 to produce a recommended calibration procedure/certificate.

31. Significant differences were observed between the EU/EASA and the other two reference CPC linearity gradients. It is noted that the North American and Swiss CPC's were calibrated concurrently and all CPC's are of the same model. It was observed that all the reference CPC displayed increased offset from linearity at the lowest traceable number limit (2000 particles/cm^3). Non-linearity is not expected therefore the authors recommend:
    - That further work (to include CPC manufacturers) is performed to assess whether the 10% linearity limit can be tightened towards 3 or 4%.
32. The CPC lower size cut-points (at D_{10} & D_{50}) were significantly different between the EU/EASA and other two reference systems, again it is noted that the North American and Swiss CPC's were calibrated concurrently and all CPC's are the same model. It is thus recommended:
    - CPC calibrated lower size cut-points (D_{10} & D_{50}) are included in a possible future PM system continuous loss function correction.
33. It was observed that altering the PCRF setting of the VPR changed the dilution corrected number concentration, though the variance was within the overall number measurement expected uncertainty, but did always move the measured number in the same direction. Therefore it is recommended:
    - That where possible on future PM system engine testing, an evaluation of different dilution settings should be performed at steady engine condition(s) to ensure that the variance stays within the expected measurement uncertainty.
34. At engine powers of 30% and below, it was not possible to operate the system at a combined (DF1 plus DF2) dilution factor so that the PM number measurement (CPC raw count) was in the AIR6241 traceably calibrated range. Therefore it is recommended that:
    - Investigate implementation of a traceable calibration methodology for <2000 particles/cm^3. For example, ISO 27891 Annex I (in final draft expect to be published 2014)
    - And/or assess the increase in number measurement uncertainty measurements if nvPM number counts are obtained below the traceable limit.
    - Investigate if commercially available VPR's could be converted to provide a lower DF2.
35. Overall the number measurement reproducibility between the 3 reference systems was generally within theoretical measurement uncertainty predictions (18 to 22%); However these 3 units were nominally identical so the uncertainty permitted by AIR 6241 may be higher than this.
36. Various biased discrepancies between the 3 systems were observed which should be further investigated, as the observed number data contradicted pre-test miniCAST comparisons. Therefore the authors recommend
    - System inter-comparisons are performed between different PM number instrument manufacturers (VPR and CPC).
    - system PM instrumentation are operated under environmental conditions recommended by manufacturers
37. All PM mass instrumentation met AIR6241 calibration performance specifications

38. It was observed that utilising diaphragm pumps in EU/EASA and North American systems caused the AVL MSS instrument to experience significant noise interference, caused by fluctuations in the sample pressure. It was noted that noise was not observed on the Swiss MSS due to the use of a buffer volume upstream of the make-up flow pump, thus this methodology was applied to both the North American and EU/EASA reference systems for the Zurich engine testing. Changing the make-up and LII pump from a diaphragm type to rotary type (for the small engine testing) removed the AVL MSS noise interference without having to install a buffer volume between the pump and instrumentation. It is thus recommended:
    - That AIR6241 instrumentation and make-up pumps specification should either limit the type of pump utilised, or control pressure fluctuations using damping volumes if an MSS is utilised in the PM measurement system. If the pressure fluctuation impact limit is known for the MSS, a performance based sampling specification could be implemented instead.
39. The AVL MSS must be run in service mode to obtain PM mass measurements on an AIR6241 compliant system if the instrument inlet pressure is lower than -80 mbarG (as observed on both the EU/EASA and North American systems). The MSS can only be used in normal conventional standard operation at instrument inlet pressures higher than -80 mbarG.
40. On Pre and Post engine test miniCAST comparisons, all the mass instruments agreed within measurement uncertainty expectations (11%).
41. Deviations larger than uncertainty expectations were observed between the mass instruments on engine PM inter-comparisons. Initial estimates of AIR6241 mass methodology uncertainty could be as large as 40 to 60% at low (<100 µg/m^3 mass instrument inlet concentrations), which reduces to ~20% at higher (>100 µg/m^3 mass instrument inlet concentrations).
42. There is some evidence that similar mass instrument types (LII vs MSS) agree better than comparing different methodologies.
43. The discrepancies observed between the PM sources (gas turbine engine and miniCAST) are under further investigation by the SAE E31 mass team including AVL.
44. At CFM56-7B26/3 engine powers of 30% and below, the mass concentration at the instrument inlet was below the AIR6241 specified 3xLOD (9 µg/m^3).
    - Require feedback from CAEP to assess whether to spend additional technical time and resource to achieve PM mass measurements at lower engine powers.
    - Operate/calibrate mass instrumentation below the existing AIR6241 LOD.
    - Possibly re-investigate feasibility of nvPM mass measurement on the GTS line
45. Representative PM data was obtained from the CFM56-7B26/3 engine. nvPM EI and size distribution data was consistent with previous PM trends observed in typical modern ‘rich burn’ engine tests in SAMPLE I, II & III campaigns. The maximum EI mass (~75 mg/kg) and largest mean particle sizes (~45 nm) were observed at the highest engine conditions. The maximum EI number (~3e14 #/kg) was observed at high powers but not at the highest. Both the lowest EI mass (which was below LOD <0.1 mg/kg) and EI number (~2.1E13) #/kg) were observed at engine conditions slightly above ground idle and had the smallest mean particle sizes (~16 nm). The EI number and EI mass increased slightly at ground idle conditions. As in line with AIR6241, these EI’s are not corrected for particle loss in the system.
46. nvPM emissions data was obtained on a small turbo shaft helicopter engine Rolls-Royce Gnome. Again a similar trend was observed with the maximum EI mass (~450

mg/kg) and largest particle sizes (~43 nm) observed at the highest engine conditions. The maximum EI number (~5E15 #/kg) was also observed at the highest engine power. Noting that the true maximum EI number would be higher due to the observed coagulation effect. Both the lowest EI mass (~18 mg/kg) and EI number (~1.4E15) #/kg) were observed at low engine power conditions above ground idle and had the smallest particle sizes (~24 nm). The EInumber and EImass increased slightly at ground idle conditions. As in line with AIR6241, these EI's are not corrected for particle loss in the system.

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10. Appendices

10.1 Calibration Certificates

10.1.1 AVL APC and TSI CPC Calibration

CPC MODEL 3790E CERTIFICATE OF CALIBRATION

3790132002	Serial Number
22-May-2013	Date

Test Aerosol: Emery Oil

Inlet Flow

		Units	Low Limit	High Limit
0.9986	Measured Flow (Volumetric)	L/min	0.95	1.05
0.703	Calculated Flow (Standard)	SL/min	-	-

Standard Conditions: 0° C, 101.3 kPa

Temperature and Pressure

		Units	Low Limit	High Limit
96.6	Room Temperature	°C	-	-
44%	Room Relative Humidity	-	-	-
96.6	Room Barometric Pressure	kPa	-	-
39	Saturator Temperature	°C	38	40
22	Condenser Temperature	°C	20	24
40	Optics Temperature	°C	39.8	40.2
32.3	Cabinet Temperature	°C	20	35
86.5	Pressure Drop Across Orifice	kPa	70	88
0.624	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
40	Laser Current Reading	mA	12	-
1.0	Minimum Pulse Height	V	1	3.65
320	Minimum Pulse Width	ns	230	950
3.3	Maximum Pulse Height	V	2	3.65
640	Maximum Pulse Width	ns	230	950

Zero Count Test

		Units	Low Limit	High Limit
0.0003	Concentration Average Over 12 Hours	p/cc	0	0.001

Lower Detection & Concentration Linearity Test Results

Value	Parameter	Units	Low Limit	High Limit
53.2%	10 nm Particle Counting Efficiency	-	50%	-
98.1%	15 nm Particle Counting Efficiency	-	90%	-
99.1%	Linearity Test: Slope (up to 10,000 p/cc)	-	90%	110%
0.9989	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	1751.90	1838.99	-4.74%	% Diff.	-10%	10%
4000 p/cc	3884.33	4000.24	-2.90%	% Diff.	-10%	10%
6000 p/cc	5785.10	5912.53	-2.16%	% Diff.	-10%	10%
8000 p/cc	7674.08	7797.78	-1.59%	% Diff.	-10%	10%
10000 p/cc	11713.06	11699.77	0.11%	% Diff.	-10%	10%

Particle Size Used in Linearity Test: 41 nm

PRD 9020519 Rev. D

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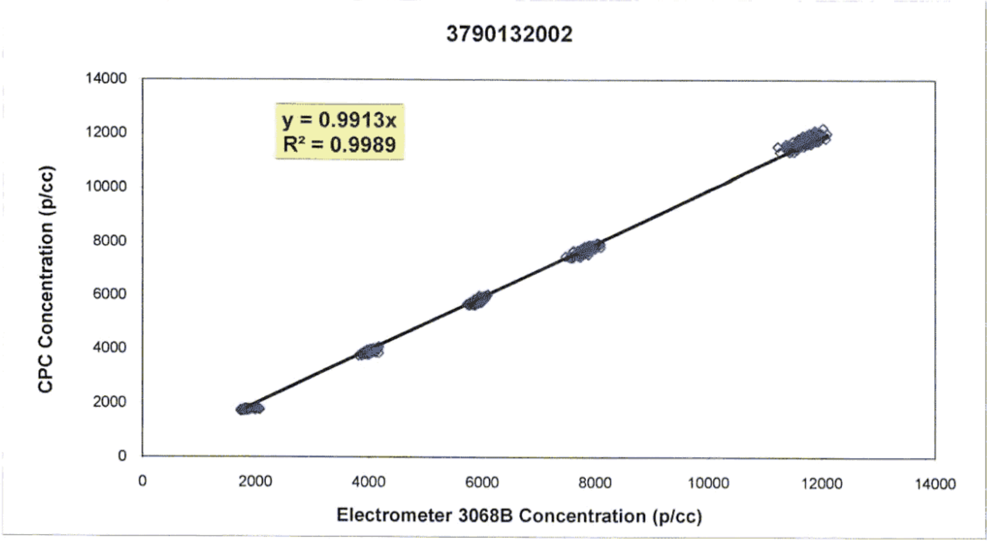
SAMPLE III

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	E003452	Jan 02, 2013	Jan 02, 2014
Voltage Measurement	E001315	Jul 09, 2012	Jan 09, 2014
Electrometer	E003432	Sep 11, 2012	Sep 11, 2013
Aerosol Flow	E001132	Oct 05, 2012	Oct 05, 2013
Classifier Flow	E003574	Aug 10, 2012	Aug 10, 2013
Temperature Measurement	E003163	Jul 13, 2012	Jul 13, 2013
Barometric Pressure Gage	E001992	Apr 04, 2013	Apr 04, 2014
Temperature/Humidity Gage	E002873	Nov 08, 2012	Nov 08, 2013

Bob Plautz
Calibrated By

22-May-2013
Calibration Date

TSI INCORPORATED

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Manufacturers Declaration of Conformity

(According to ISO/IEC Guide 22 and EN 45014)

TSI Incorporated does hereby declare that, to the best of its knowledge and belief, the products referenced below meets the essential requirements and is in conformity with the relevant EC Directive(s) listed using the relevant section of the EC Standard. The required performance and safety tests were successfully conducted according to the harmonized standards. The CE Marking has been affixed on the device(s) according to the EC Directives.

Manufacturer's Contact:

September 18, 2012

Date

Thomas E. Jacobson
Vice President of Operations

Product Name	Model(s)	Safety Directive 2006/95/EC Standard Used	Emissions Directive 2004/108/EC Standards Used	Immunity Directive 2004/108/EC Standard Used
Particle Instruments				
TSI Engine Exhaust Particle Sizer®	3790 3791 3792	EN61010-1:2001	EN61326-1:2006 Class B	EN61326-1:2006

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Calibration values set in firmware

Directly measured values for the seven fixed PCRF settings

PCRF	calib. value
100	1,19
250	1,10
500	1,09
1000	1,08
1500	1,10
2000	1,12
3000	1,08

Interpolated values for variable PCRF settings*

Diluter 1 low	
Diluter 2	**calib. value**
10	1,16
15	1,13
20	1,17

Pressures during calibration

Sample Rel. Pressure	-48 mbar
Diluted. Rel. Pressure	37 mbar
Absolute Pressure	972 mbar

Demand temperatures during calibration

Catalytic Stripper Temperature	300 °C
Diluter 1 Temperature	150 °C

* 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 Advanced Calibration Certificate

Date: 4-Jun-2013		
Device: GH0672		382
	Chopper Diluter	460

Makro	XF0339	V1.26

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	4497 ml/min	25°C; 1013.25mbar
Master CPC	995 ml/min	ambient conditons

Zero Concentration with HEPA-Filter		
APC	0,07 #/cm³	at pcrf=10*10=100
Master CPC	0,000 #/cm³	

	values set				Factor	values measured				
Nr	Diluter 1 low/high	Diluter 1	Diluter 2	set pcrf	pcrf_mes/ pcrf_set	measured pcrf	σ/pcrf rel. error	$pcrf_{(30nm)}/pcrf_{(100nm)}$	$pcrf_{(50nm)}/pcrf_{(100nm)}$	$pcrf_{(100nm)}$
1	low	10	10	**100**	**1,19**	**119**	**0,2%**	1,16	1,09	110
2	low	25	10	**250**	**1,10**	**276**	**0,2%**	1,14	1,06	259
3	low	50	10	**500**	**1,09**	**544**	**0,3%**	1,14	1,08	507
4	low	100	10	**1000**	**1,08**	**1083**	**0,5%**	1,15	1,08	1006
5	low	150	10	**1500**	**1,10**	**1645**	**0,6%**	1,19	1,05	1523
6	low	200	10	**2000**	**1,12**	**2239**	**0,7%**	1,23	1,11	2010
7	low	200	15	**3000**	**1,08**	**3237**	**0,8%**	1,17	1,06	3012
8	low	10	15	**150**	**1,18**	**177**	**0,2%**	1,16	1,08	164
9	low	10	20	**200**	**1,20**	**239**	**0,2%**	1,18	1,10	219
10	low	200	20	**4000**	**1,14**	**4558**	**0,7%**	1,20	1,10	4139
Volatile Particle Removal Efficiency for Tetracontane:					**99,98%**					

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)

10.1.2 Mass Flow Controllers

Bronkhorst®

CALIBRATION CERTIFICATE

FLUID NO. 1 OF 1

CERTIFICATE NO. BHTG18/1443260

Calibration by comparison
Calibration date: 6 May 2013

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	Piston Prover
Serial number	80050
Certificate no.	BCC001/1282323
Uncertainty	±0.3% Rd

Customer conditions

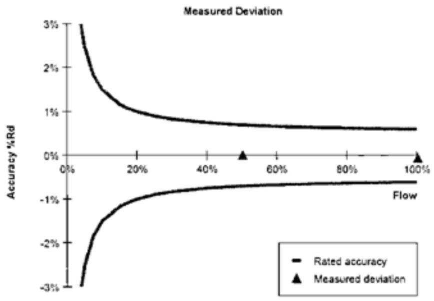
Fluid	**AiR**
Flow	**12.50 ls/min**
Pressure	**900.0 mbar (a)**
Temperature	**5.0..40.0 °C**

Calibration conditions

Fluid	AiR
Flow	12.45 ls/min (equivalent flow)
Pressure	5.0 bar (a)
Temperature	23.1 °C
Atm. pressure	1017.8 hPa (a)

Calibration and conversion results

Output signal	Customer flow** AiR	Equivalent flow** AiR	Reference flow AiR	Measured deviation*	Measurement uncertainty*
100.35%	12.54 ls/min	12.49 ls/min	12.50 ls/min	-0.06 % Rd	0.4 % Rd
50.24%	6.281 ls/min	6.255 ls/min	6.254 ls/min	0.01 % 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.

More detailed information about the used calibration method can be found on http://www.bronkhorst.com/certificates.

Calibrator R.Mu.

QC A.F.K.
Date 13 May 2013
Signed ....

MultiCal V1.48 FLUIDAT® V5.73 (Database: 05-05-1999) Report V1.12

Bronkhorst®
HIGH-TECH

CALIBRATION CERTIFICATE

FLUID NO. 1 OF 1
CERTIFICATE NO. BHTG18/1443264

Calibration by comparison
Calibration date: 6 May 2013

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	Piston Prover
Serial number	80050
Certificate no.	BCC001/1282323
Uncertainty	±0.3% Rd

Customer conditions

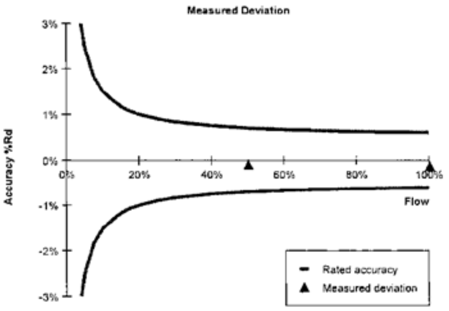
Fluid	**AiR**
Flow	**12.50 ls/min**
Pressure	**900.0 mbar (a)**
Temperature	**5.0..40.0 °C**

Calibration conditions

Fluid	AiR
Flow	12.45 ls/min (equivalent flow)
Pressure	5.0 bar (a)
Temperature	23.1 °C
Atm. pressure	1017.8 hPa (a)

Calibration and conversion results

Output signal	Customer flow** AiR	Equivalent flow** AiR	Reference flow AiR	Measured deviation*	Measurement uncertainty*
100.27%	12.53 ls/min	12.48 ls/min	12.50 ls/min	-0.13 % Rd	0.4 % Rd
50.19%	6.274 ls/min	6.248 ls/min	6.254 ls/min	-0.09 % 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.

More detailed information about the used calibration method can be found on http://www.bronkhorst.com/certificates.

Calibrator R.Mu.

QC A.F.K.
Date 13 May 2013
Signed ....

MultiCal V1.46 FLUIDAT® V5.73 (Database: 05-05-1999) Report V1.12

Bronkhorst®
HIGH-TECH

CALIBRATION CERTIFICATE

FLUID NO. 1 OF 1
CERTIFICATE NO. BHTG18/1443262

Calibration by comparison
Calibration date: 6 May 2013

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	Piston Prover
Serial number	80050
Certificate no.	BCC001/1282323
Uncertainty	±0.3% Rd

Customer conditions

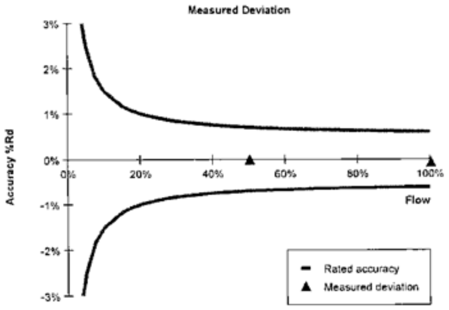
Fluid	AiR
Flow	**12.50 ls/min**
Pressure	**900.0 mbar (a)**
Temperature	**5.0..40.0 °C**

Calibration conditions

Fluid	AiR
Flow	12.45 ls/min (equivalent flow)
Pressure	5.0 bar (a)
Temperature	23.1 °C
Atm. pressure	1017.8 hPa (a)

Calibration and conversion results

Output signal	Customer flow** AiR	Equivalent flow** AiR	Reference flow AiR	Measured deviation*	Measurement uncertainty*
100.34%	12.54 ls/min	12.49 ls/min	12.50 ls/min	-0.06 % Rd	0.4 % Rd
50.24%	6.280 ls/min	6.254 ls/min	6.254 ls/min	0.00 % 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.

More detailed information about the used calibration method can be found on http://www.bronkhorst.com/certificates.

Calibrator R.Mu.

QC A.F.K.
Date 13 May 2013
Signed ....

MultiCal V1.48 FLUIDAT® V5.73 (Database: 05-05-1999) Report V1.12

10.2 Example of new proposed AIR 6241 calibration certification that may be used by AVL in the future

AVL 489 Particle Counter Advanced Calibration Certificate

AVL

Date:	4-Oct-2012	
Device:	GH0672	409
	Chopper Diluter	507

Makro	XF0339	V1.26

Used Instruments	Type	Serial No.
DMA	TSI 3080N	70838176
Master CPC	TSI 3772	71025293
Mass Flow Meter	RedY GCR-B5SA-BA25	115467
Calibration aerosol: Mini CAST combustion soot		

Measured Inlet Flows of Instruments		
Device	Vol. Flow	Normalization Cond.
APC Chopper Dil. low	4610 ml/min	25°C; 1013.25mbar
APC Chopper Dil. high	4530 ml/min	25°C; 1013.25mbar
Master CPC	1026 ml/min	ambient conditons

Zero Concentration with HEPA-Filter		
APC	0.07 #/cm³	at pcrf=10*10=100
Master CPC	0.000 #/cm³	

Nr	values set: Diluter 1 low/high	Diluter 1	Diluter 2	set pcrf	Flows Dilution Factor	Measured penetrations: 100 nm	50 nm	30 nm	15 nm
1	low	10	10	**100**	66	73%	67%	60%	30%
2	low	25	10	**250**	175	77%	71%	62%	33%
3	low	50	10	**500**	350	77%	72%	62%	32%
4	low	100	10	**1000**	693	77%	71%	62%	32%
5	low	150	10	**1500**	1029	75%	72%	60%	30%
6	low	200	10	**2000**	1317	74%	68%	57%	31%
7	low	200	15	**3000**	2025	76%	70%	58%	32%
8	low	10	15	**150**	100	72%	69%	61%	30%
9	low	10	20	**200**	134	73%	69%	60%	30%
10	low	200	20	**4000**	2694	74%	70%	60%	31%

Example Values Only

Volatile Particle Removal Efficiency for Tetracontane: 99.99%

SAMPLE III

AVL 489 Particle Counter Advanced Calibration Certificate

AVL

Date:	4-Oct-2012	
Device:	GH0672	409
	Chopper Diluter	507

Makro	XF0339	V1.26

Used Instruments	Type	Serial No.
DMA	TSI 3080N	70838176
Master CPC	TSI 3772	71025293
Mass Flow Meter	RedY GCR-B5SA-BA25	115467
Calibration aerosol: Mini CAST combustion soot		

Measured Inlet Flows of Instruments		
Device	Vol. Flow	Normalization Cond.
APC Chopper Dil. low	4610 ml/min	25°C; 1013.25mbar
APC Chopper Dil. high	4530 ml/min	25°C; 1013.25mbar
Master CPC	1026 ml/min	ambient conditons

Zero Concentration with HEPA-Filter		
APC	0.07 #/cm³	at pcrf=10*10=100
Master CPC	0.000 #/cm³	

Nr	values set				Flows	Measured penetrations			
	Diluter 1 low/high	Diluter 1	Diluter 2	set pcrf	Dilution Factor	100 nm	50 nm	30 nm	15 nm
1	low	10	10	**100**	66	73%	67%	60%	30%
2	low	25	10	**250**	175	77%	71%	62%	33%
3	low	50	10	**500**	350	77%	72%	62%	32%
4	low	100	10	**1000**	693	77%	71%	62%	32%
5	low	150	10	**1500**	1029	75%	72%	60%	30%
6	low	200	10	**2000**	1317	74%	68%	57%	31%
7	low	200	15	**3000**	2025	76%	70%	58%	32%
8	low	10	15	**150**	100	72%	69%	61%	30%
9	low	10	20	**200**	134	73%	69%	60%	30%
10	low	200	20	**4000**	2694	74%	70%	60%	31%
Volatile Particle Removal Efficiency for Tetracontane:					99.99%				

Example Values Only

10.3 Fuel Certificates

Intertek (Schweiz) AG
www.betriebsstoffe.ch
www.intertek.com
Wagistrasse 2 CH-8952 Schlieren Fon:+41-43 433 78 10 Fax:+41-43 433 78 19 schlieren@intertek.com

Test Report No: 113063/07 **Page 1 of 1**

Client:

Empa
Materials Science & Technology
Abt. Analytische Chemie
Überlandstrasse 129
CH-8600 Dübendorf

Test object:	**Jet A-1**
Date of Receipt:	2013-08-13
Container:	1 can
Order from:	2013-08-13
Origin:	Triebwerkprüfstand
Date of Sampling:	12.08.2013
Compiler:	Beni Brem
Specification:	Joint Fuelling System Check List Jet A-1 (AFQRJOS) Issue 27 - Feb 2013

Property	Unit	Result	Limits Low	Limits High	Test Method
Aromatics	% (V/V)	18,0		25,0	ASTM D 1319
Sulfur, total	% (m/m)	0,039		0,30	ASTM D 5453
Distillation (101,3 kPa)					ASTM D 86
Initial boiling point	°C	151			
10 Vol % recovered at	°C	168		205,0	
20 Vol % recovered at	°C	174			
50 Vol % recovered at	°C	193			
90 Vol % recovered at	°C	235			
End point	°C	261		300,0	
Residue	% (V/V)	1,1		1,5	
Loss	% (V/V)	0,7		1,5	
Density at 15 °C	kg/m³	797,8	775,0	840,0	ASTM 4052
Viscosity at -20 °C	mm²/s	3,596		8,000	ASTM D 445
Specific energy, net	MJ/kg	43,3	42,80		ASTM D 3338
Smoke point	mm	21,0	19,0		ASTM D 1322
Naphthalenes	% (V/V)	0,71		3,00	ASTM D 1840
Hydrogen	% (m/m)	14,04			ASTM D 5291

Schlieren, 21.08.2013

Project Leader: U. Debrunner

General Manager: Dr. H.W. Jäckle

SWISS TESTING
STS-Nr. 452
Februar 2006

Remark: The test results are only valid for the analysed sample. The utilisation of the report for advertising purposes, or reference to it in publications, requires the permission of Intertek (Schweiz) AG. Details of the analyses (norms, SOPs), as well as limits of detection and standard deviations can be obtained from Intertek (Schweiz) AG. Files, including reports, are retained for ten years at Intertek (Schweiz) AG. The raw data is held at Intertek (Schweiz) AG for ten years. The sample is held at Intertek (Schweiz) AG for at least one month after the report has been completed.

[1] Subconctractor, [2] Method not accredited

200092929-120607-UD

Intertek (Schweiz) AG
www.betriebsstoffe.ch
www.intertek.com
Wagistrasse 2 CH-8952 Schlieren Fon:+41-43 433 78 10 Fax:+41-43 433 78 19 schlieren@intertek.com

Test Report No: 113063/08

Client:

Empa
Materials Science & Technology
Abt. Analytische Chemie
Überlandstrasse 129
CH-8600 Dübendorf

Test object:	**Jet A-1**
Date of Receipt:	2013-08-13
Container:	1 can
Order from:	2013-08-13
Origin:	Testcell
Date of Sampling:	29.07.2013
Compiler:	Beni Brem
Specification:	Joint Fuelling System Check List Jet A-1 (AFQRJOS) Issue 27 - Feb 2013

Property	Unit	Result	Limits Low	Limits High	Test Method
Aromatics	% (V/V)	17,7		25,0	ASTM D 1319
Sulfur, total	% (m/m)	0,053		0,30	ASTM D 5453
Distillation (101,3 kPa)					ASTM D 86
Initial boiling point	°C	155			
10 Vol % recovered at	°C	169		205,0	
20 Vol % recovered at	°C	175			
50 Vol % recovered at	°C	193			
90 Vol % recovered at	°C	236			
End point	°C	265		300,0	
Residue	% (V/V)	1,1		1,5	
Loss	% (V/V)	0,5		1,5	
Density at 15 °C	kg/m³	797,6	775,0	840,0	ASTM 4052
Viscosity at -20 °C	mm²/s	3,591		8,000	ASTM D 445
Specific energy, net	MJ/kg	43,3	42,80		ASTM D 3338
Smoke point	mm	21,0	19,0		ASTM D 1322
Naphthalenes	% (V/V)	0,68		3,00	ASTM D 1840
Hydrogen	% (m/m)	14,18			ASTM D 5291

Schlieren, 21.08.2013

Project Leader: U. Debrunner

General Manager: Dr. H.W. Jäckle

SWISS TESTING
STS-Nr. 452
Februar 2006

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[1] Subconctractor, [2] Method not accredited

200092930-120607-UD

SAMPLE III

Intertek

Intertek (Schweiz) AG
www.betriebsstoffe.ch
www.intertek.com
Wagistrasse 2 CH-8952 Schlieren Fon:+41-43 433 78 10 Fax:+41-43 433 78 19 schlieren@intertek.com

Test Report No: 113063/09

Client:

Empa
Materials Science & Technology
Abt. Analytische Chemie
Überlandstrasse 129
CH-8600 Dübendorf

Test object:	**Jet A-1**
Date of Receipt:	2013-08-13
Container:	1 can
Order from:	2013-08-13
Origin:	TW-Prüfstand
Date of Sampling:	05.08.2013
Compiler:	Beni Brem
Specification:	Joint Fuelling System Check List Jet A-1 (AFQRJOS) Issue 27 - Feb 2013

Property	Unit	Result	Limits Low	Limits High	Test Method
Aromatics	% (V/V)	17,4		25,0	ASTM D 1319
Sulfur, total	% (m/m)	0,039		0,30	ASTM D 5453
Distillation (101,3 kPa)					ASTM D 86
Initial boiling point	°C	155			
10 Vol % recovered at	°C	168		205,0	
20 Vol % recovered at	°C	174			
50 Vol % recovered at	°C	193			
90 Vol % recovered at	°C	236			
End point	°C	265		300,0	
Residue	% (V/V)	1,1		1,5	
Loss	% (V/V)	0,8		1,5	
Density at 15 °C	kg/m³	797,8	775,0	840,0	ASTM 4052
Viscosity at -20 °C	mm²/s	3,598		8,000	ASTM D 445
Specific energy, net	MJ/kg	43,3	42,80		ASTM D 3338
Smoke point	mm	21,0	19,0		ASTM D 1322
Naphthalenes	% (V/V)	0,71		3,00	ASTM D 1840
Hydrogen	% (m/m)	14,28			ASTM D 5291

Schlieren, 21.08.2013

Project Leader: General Manager:

U. Debrunner Dr. H.W. Jäckle

SWISS TESTING
STS-Nr. 452
Februar 2006

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[1] Subconctractor, [2] Method not accredited

200092931-120607-UD

SAMPLE III

Intertek (Schweiz) AG
www.betriebsstoffe.ch
www.intertek.com
Wagistrasse 2 CH-8952 Schlieren Fon:+41-43 433 78 10 Fax:+41-43 433 78 19 schlieren@intertek.com

Test Report No: 113063/10

Client:

Empa
Materials Science & Technology
Abt. Analytische Chemie
Überlandstrasse 129
CH-8600 Dübendorf

Test object:	**Jet A-1**
Date of Receipt:	2013-08-13
Container:	1 can
Order from:	2013-08-13
Origin:	Tanker Probe
Date of Sampling:	02.08.2013
Compiler:	Beni Brem
Specification:	Joint Fuelling System Check List Jet A-1 (AFQRJOS) Issue 27 - Feb 2013

Property	Unit	Result	Limits Low	Limits High	Test Method
Aromatics	% (V/V)	17,7		25,0	ASTM D 1319
Sulfur, total	% (m/m)	0,033		0,30	ASTM D 5453
Distillation (101,3 kPa)					ASTM D 86
Initial boiling point	°C	151			
10 Vol % recovered at	°C	168		205,0	
20 Vol % recovered at	°C	174			
50 Vol % recovered at	°C	193			
90 Vol % recovered at	°C	236			
End point	°C	265		300,0	
Residue	% (V/V)	1,1		1,5	
Loss	% (V/V)	0,6		1,5	
Density at 15 °C	kg/m³	797,7	775,0	840,0	ASTM 4052
Viscosity at -20 °C	mm²/s	3,618		8,000	ASTM D 445
Specific energy, net	MJ/kg	43,3	42,80		ASTM D 3338
Smoke point	mm	21,0	19,0		ASTM D 1322
Naphthalenes	% (V/V)	0,72		3,00	ASTM D 1840
Hydrogen	% (m/m)	14,18			ASTM D 5291

Schlieren, 21.08.2013

Project Leader: General Manager:

U. Debrunner Dr. H.W. Jäckle

SWISS TESTING
STS-Nr. 452
Februar 2006

[1] Subconctractor, [2] Method not accredited

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www.betriebsstoffe.ch
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Wagistrasse 2 CH-8952 Schlieren Fon:+41-43 433 78 10 Fax:+41-43 433 78 19 schlieren@intertek.com

Test Report No: 113063/11

Client:

Empa
Materials Science & Technology
Abt. Analytische Chemie
Überlandstrasse 129
CH-8600 Dübendorf

Test object:	**Jet A-1**
Date of Receipt:	2013-08-27
Container:	1 can
Order from:	2013-08-27
Origin:	Prüfstand
Date of Sampling:	25.08.2013
Compiler:	Beni Brem
Specification:	Joint Fuelling System Check List Jet A-1 (AFQRJOS) Issue 27 - Feb 2013

Property	Unit	Result	Limits Low	Limits High	Test Method
Aromatics	% (V/V)	17,5		25,0	ASTM D 1319
Sulfur, total	% (m/m)	0,042		0,30	ASTM D 5453
Distillation (101,3 kPa)					ASTM D 86
Initial boiling point	°C	153			
10 Vol % recovered at	°C	169		205,0	
20 Vol % recovered at	°C	174			
50 Vol % recovered at	°C	193			
90 Vol % recovered at	°C	235			
End point	°C	264		300,0	
Residue	% (V/V)	1,2		1,5	
Loss	% (V/V)	0,6		1,5	
Density at 15 °C	kg/m³	797,2	775,0	840,0	ASTM 4052
Viscosity at -20 °C	mm²/s	3,618		8,000	ASTM D 445
Specific energy, net	MJ/kg	43,3	42,80		ASTM D 3338
Smoke point	mm	22,0	19,0		ASTM D 1322
Naphthalenes	% (V/V)	0,70		3,00	ASTM D 1840
Hydrogen	% (m/m)	13,76			ASTM D 5291

Schlieren, 12.09.2013

Project Leader: General Manager:

U. Debrunner Dr. H.W. Jäckle

SWISS TESTING
STS-Nr. 452
Februar 2006

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[1] Subconctractor, [2] Method not accredited

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Wagistrasse 2 CH-8952 Schlieren Fon:+41-43 433 78 10 Fax:+41-43 433 78 19 schlieren@intertek.com

Test Report No: 113063/12

Client:

Empa
Materials Science & Technology
Abt. Analytische Chemie
Überlandstrasse 129
CH-8600 Dübendorf

Test object:	**Jet A-1**
Date of Receipt:	2013-08-27
Container:	1 can
Order from:	2013-08-27
Sample designation:	1
Date of Sampling:	13.08.2013
Compiler:	Beni Brem
Specification:	Joint Fuelling System Check List Jet A-1 (AFQRJOS) Issue 27 - Feb 2013

			Limits		
Property	**Unit**	**Result**	**Low**	**High**	**Test Method**
Aromatics	% (V/V)	17,7		25,0	ASTM D 1319
Sulfur, total	% (m/m)	0,042		0,30	ASTM D 5453
Distillation (101,3 kPa)					ASTM D 86
Initial boiling point	°C	149			
10 Vol % recovered at	°C	167		205,0	
20 Vol % recovered at	°C	173			
50 Vol % recovered at	°C	193			
90 Vol % recovered at	°C	234			
End point	°C	263		300,0	
Residue	% (V/V)	1,1		1,5	
Loss	% (V/V)	0,4		1,5	
Density at 15 °C	kg/m³	797,8	775,0	840,0	ASTM 4052
Viscosity at -20 °C	mm²/s	3,599		8,000	ASTM D 445
Specific energy, net	MJ/kg	43,3	42,80		ASTM D 3338
Smoke point	mm	22,0	19,0		ASTM D 1322
Naphthalenes	% (V/V)	0,74		3,00	ASTM D 1840
Hydrogen	% (m/m)	13,96			ASTM D 5291

Schlieren, 12.09.2013

Project Leader: General Manager:

U. Debrunner Dr. H.W. Jäckle

STS-Nr. 452
Februar 2006

Remark: The test results are only valid for the analysed sample. The utilisation of the report for advertising purposes, or reference to it in publications, requires the permission of Intertek (Schweiz) AG. Details of the analyses (norms, SOPs), as well as limits of detection and standard deviations can be obtained from Intertek (Schweiz) AG. Files, including reports, are retained for ten years at Intertek (Schweiz) AG. The raw data is held at Intertek (Schweiz) AG for ten years. The sample is held at Intertek (Schweiz) AG for at least one month after the report has been completed.

[1] Subconctractor, [2] Method not accredited

200093069-120607-UD

Intertek (Schweiz) AG
www.betriebsstoffe.ch
www.intertek.com
Wagistrasse 2 CH-8952 Schlieren Fon:+41-43 433 78 10 Fax:+41-43 433 78 19
schlieren@intertek.com

Test Report No: 113063/13

Client:

Empa
Materials Science & Technology
Abt. Analytische Chemie
Überlandstrasse 129
CH-8600 Dübendorf

Test object:	**Jet A-1**
Date of Receipt:	2013-08-27
Container:	1 can
Order from:	2013-08-27
Sample designation:	2
Date of Sampling:	13.08.2013
Compiler:	Beni Brem
Specification:	Joint Fuelling System Check List Jet A-1 (AFQRJOS) Issue 27 - Feb 2013

Property	Unit	Result	Limits Low	Limits High	Test Method
Aromatics	% (V/V)	17,7		25,0	ASTM D 1319
Sulfur, total	% (m/m)	0,042		0,30	ASTM D 5453
Distillation (101,3 kPa)					ASTM D 86
Initial boiling point	°C	152			
10 Vol % recovered at	°C	168		205,0	
20 Vol % recovered at	°C	174			
50 Vol % recovered at	°C	193			
90 Vol % recovered at	°C	235			
End point	°C	264		300,0	
Residue	% (V/V)	1,1		1,5	
Loss	% (V/V)	0,5		1,5	
Density at 15 °C	kg/m³	797,8	775,0	840,0	ASTM 4052
Viscosity at -20 °C	mm²/s	3,599		8,000	ASTM D 445
Specific energy, net	MJ/kg	43,3	42,80		ASTM D 3338
Smoke point	mm	21,0	19,0		ASTM D 1322
Naphthalenes	% (V/V)	0,75		3,00	ASTM D 1840
Hydrogen	% (m/m)	14,00			ASTM D 5291

Schlieren, 12.09.2013

Project Leader: U. Debrunner

General Manager: Dr. H.W. Jäckle

SWISS TESTING
STS-Nr. 452
Februar 2006

Remark: The test results are only valid for the analysed sample. The utilisation of the report for advertising purposes, or reference to it in publications, requires the permission of Intertek (Schweiz) AG. Details of the analyses (norms, SOPs), as well as limits of detection and standard deviations can be obtained from Intertek (Schweiz) AG. Files, including reports, are retained for ten years at Intertek (Schweiz) AG. The raw data is held at Intertek (Schweiz) AG for ten years. The sample is held at Intertek (Schweiz) AG for at least one month after the report has been completed.

¹ Subconctractor, ² Method not accredited

200093070-120607-UD

10.4 Span & Zero Gas Certificates

Carbagas

Carbagas AG Bern Basel Zürich Lausanne Geneve
Hofgut 3073 Gumligen Tel. 031 950 50 50 Fax 031 950 50 52
www.carbagas.ch info@carbagas.ch MWSt N°/Id TVA 121739

CERTIFICAT D'ANALYSE
N°: 1356344

N° client :	**1277354**
N° commande client :	
N° commande interne :	**131911120**
Type d'emballage :	**10.0 l. Aluminium**
N° de bouteille :	**4767**
Pression finale :	**150 bar**
Raccord vanne :	**DIN 477 / 6**
Pression min. utilisation :	**2 bar**
Temp. Minimum :	**-10 °C**
Garantie de stabilité :	**24 mois**
Classe de réalisation:	**Saphir**

Client :	**SR Technics Warenannahme**
Adresse :	**Hangarstrasse / Tor 140**
Localité :	**8058 Zürich Flughafen**
Réf. :	**Eng. Test Cell 01/ZR**
Région:	**RUM**

			CONCENTRATION MOLAIRE		
N°	Composant	Qualité	Demandée	Réalisée	Incertitude +/-
1	CO2	40	4.50%	4.49%	1.00 % rel.
2	O2	35	19.10%	19.13%	1.00 % rel.
3	N2	50	Reste		

Domdidier, le 28.06.13

A. Camélique

A Caméliqu

Page 1 de 1

AIR LIQUIDE

Carbagas AG Bern Basel Zürich Lausanne Genève
Hofgut 3073 Gümligen Tel. 031 950 50 50 Fax 031 950 50 52
www.carbagas.ch info@carbagas.ch MWST N°/TVA 121739

CERTIFICAT D'ANALYSE
N°: 1356343

N° client : **1277354**
N° commande client :
N° commande interne : **131911105**
Type d'emballage : **10.0 l. Aluminium**
N° de bouteille : **9407**
Pression finale : **150 bar**
Raccord vanne : **DIN 6 W21.8x1.14"**
Pression min. utilisation : **2 bar**
Temp. Minimum : **-10 °C**
Garantie de stabilité : **24 mois**
Classe de réalisation: **Saphir**

Client : **SR Technics Warenannahme**
Adresse : **Hangarstrasse / Tor 140**
Localité : **8058 Zürich Flughafen**
Réf. : **Eng. Test Cell 01/ZR**
Région: **RUM**

			CONCENTRATION MOLAIRE		
N°	Composant	Qualité	Demandée	Réalisée	Incertitude +/-
1	CO_2	40	25.0ppm	25.2ppm	2.00 % rel.
2	O_2	48	20.00%	19.97%	2.00 % rel.
3	N_2	57	Reste		

Domdidier, le 03.07.13

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SAMPLE III

Carbagas

Carbagas AG Bern Basel Zürich Lausanne Genève
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www.carbagas.ch info@carbagas.ch MWSt Nr/Id TVA 121739

CERTIFICAT D'ANALYSE
N°: 1356345

N° client : **1277354**
N° commande client :
N° commande interne : **131911133**
Type d'emballage : **10.0 l. Aluminium**
N° de bouteille : **4305**
Pression finale : **150 bar**
Raccord vanne : **DIN 6 W21.8x1.14"**
Pression min utilisation : **2 bar**
Temp. Minimum : **0 °C**
Garantie de stabilité : **24 mois**
Classe de réalisation: **Saphir**

Client : **SR Technics Warenannahme**
Adresse : **Hangarstrasse / Tor 140**
Localité : **8058 Zürich Flughafen**
Réf. : **Eng. Test Cell 01/ZR**
Région: **RUM**

			CONCENTRATION MOLAIRE		
N°	Composant	Qualité	Demandée	Réalisée	Incertitude +/-
1	**CO2**	**40**	**50.0ppm**	**50.1ppm**	**2.00 % rel.**
2	**O2**	**35**	**19.999%**	**20.03%**	**2.00 % rel.**
3	**N2**	**50**	**Reste**		

Domdidier, le 03.07.13

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SAMPLE III

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CERTIFICAT D'ANALYSE

N°: 1356346

N° client :	1277354
N° commande client :	
N° commande interne :	131911219
Type d'emballage :	10.0 l. Aluminium
N° de bouteille :	1118
Pression finale :	150 bar
Raccord vanne :	DIN 6 W21.8x1.14"
Pression min. utilisation :	2 bar
Temp. Minimum :	-10 °C
Garantie de stabilité :	24 mois
Classe de réalisation:	Saphir

Client :	SR Technics Warenannahme
Adresse :	Hangarstrasse / Tor 140
Localité :	8058 Zürich Flughafen
Réf. :	Eng. Test Cell 01/ZR
Région:	RUM

			CONCENTRATION MOLAIRE		
N°	Composant	Qualité	Demandée	Réalisée	Incertitude +/-
1	CO2	40	75.0ppm	75.1ppm	2.00 % rel.
2	O2	48	20.00%	19.99%	2.00 % rel.
3	N2	57	Reste		

Domdidier, le 03.07.13

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Carbagas

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Hofgut 3073 Gümligen Tel 031 950 50 50 Fax 031 950 50 52
www.carbagas.ch info@carbagas.ch MWS: N°/Id TVA 121739

CERTIFICAT D'ANALYSE
N°: 1356347

N° client :	**1277354**
N° commande client :	
N° commande interne :	**131911242**
Type d'emballage :	**10.0 l. Aluminium**
N° de bouteille :	**4338**
Pression finale :	**150 bar**
Raccord vanne :	**DIN 477 / 6**
Pression min. utilisation :	**2 bar**
Temp. Minimum :	**-10 °C**
Garantie de stabilité :	**24 mois**
Classe de réalisation:	**Saphir**

Client :	**SR Technics Warenannahme**
Adresse :	**Hangarstrasse / Tor 140**
Localité :	**8058 Zürich Flughafen**
Réf. :	**Eng. Test Cell 01/ZR**
Région:	**RUM**

			CONCENTRATION MOLAIRE		
N°	Composant	Qualité	Demandée	Réalisée	Incertitude +/-
1	**CO_2**	**40**	**0.45%**	**0.4495%**	**1.00 % rel.**
2	**O_2**	**35**	**20.70%**	**20.712%**	**1.00 % rel.**
3	**N_2**	**50**	**Reste**		

Domdidier, le 01.07.13

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A. Camélique

AIR LIQUIDE

SAMPLE III

Carbagas

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Hofgut 3073 Gümligen Tel 031 950 50 50 Fax 031 950 50 52
www.carbagas.ch info@carbagas.ch MWST Nr/No TVA 121739

CERTIFICAT DE CONTRÔLE
N°: 1356379

N° client : **1277354**
N° commande client :
N° commande interne : **131924940**
Type d'emballage : **50.0 l. Acier**
N° de bouteille : **505338**
Pression finale : **150 bar**
Raccord vanne : **DIN 477 / 6**
Pression min. utilisation : **2 bar**
Temp. Minimum : **-10 °C**
Garantie de stabilité : **24 mois**
Classe de réalisation: **Blue**

Client : **SR Technics Warenannahme**
Adresse : **Hangarstrasse / Tor 140**
Localite : **8058 Zürich Flughafen**
Réf. : **Eng. Test Cell 01/ZR**
Région: **RUM**

			CONCENTRATION MOLAIRE
N°	Composant	Qualité	Nominale
1	**O2**	**55**	**20.00%**
2	**N2**	**60**	**Reste**

Domdidier, le 26.06.13

M. Duc

10.5 AVL report on APC exhaust geometry sensitivity immunity

AVL List GmbH
Hans-List-Platz 1,
A-8020 Graz
Austria
www.avl.com
Technical Memo 28 May 2014: report on experiments showing the immunity of APC to downstream pressure variations
Christos Dardiotis AVL/AT, William Silvis AVL/US

Report on experiments showing the immunity of APC to downstream pressure variations

AVL List GmbH
Hans-List-Platz 1,
A-8020 Graz
Austria
www.avl.com
Technical Memo 28 May 2014: report on experiments showing the immunity of APC to downstream pressure variations
Christos Dardiotis AVL/AT, William Silvis AVL/US

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AVL List GmbH
Hans-List-Platz 1,
A-8020 Graz
Austria
www.avl.com
Technical Memo 28 May 2014: report on experiments showing the immunity of APC to downstream pressure variations
Christos Dardiotis AVL/AT, William Silvis AVL/US

1. INTRODUCTION

In December 2013 it was reported at E31-meeting (Tullahoma TN, USA) that when a tube of more than 35 cm and/or a CO_2 gas analyser are connected at the Exhaust Secondary Dilution of the AVL Particle Counter (APC) the concentration of the Condensation Particle Counter (CPC) is affected (Figure 1). The scope of the document is to describe the tests that were done to verify the immunity of APC measured particle concentration on pressure variations due to the geometry of "exhaust sec. dil." outlet tube.

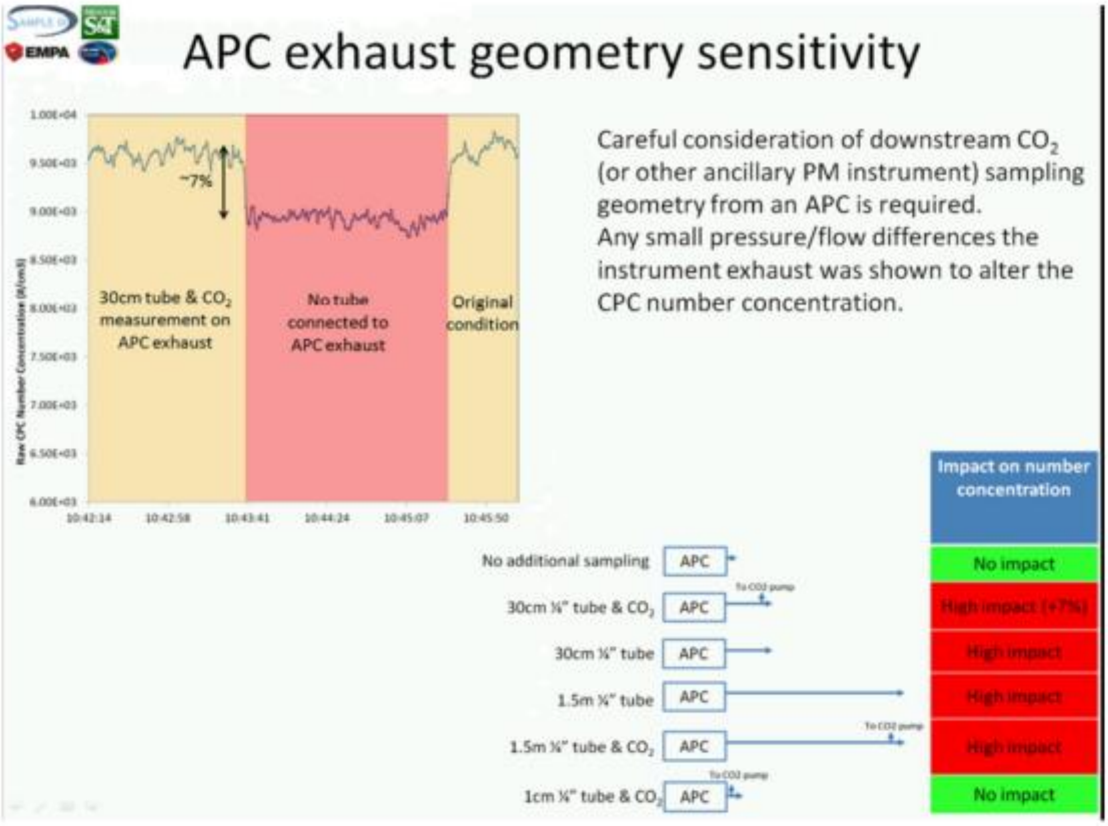

Figure 1: Effect of Exhaust Secondary Dilution tube configuration on CPC concentration.

2. EXPERIMENTAL

The experiments were done at AVL/Graz Optic Lab (UK02). An AVL Particle Generator (APG s/n: PT1) was used to create combustion particles. The (E31 compliant) APC (s/n: 307C) was fed with polydisperse exhaust gas produced by the APG [1], with a mean size distribution of ~100 nm. The APC was tested using two different Dilution Factors (DF): 178 and 2020 representing Particle Concentration Reduction Factor (PCRF) 250 and 3000 respectively. The

DFs that were used cause different flow through the APC excess outlet, 9 and 14 l/min respectively, due to different secondary dilution employed. Two different tubes were connected at the exhaust secondary dilution:

- Tygon R-3400, 1/4" diameter (6.35 mm), 1.33 m length
- Teflon, 4 mm diameter, 2.5 m length

The material of the tubes is not expected to influence the pressure drop. The diameter and the length of the tubes affect the pressure drop and/or other APC/CPC operational characteristics. The experimental setup is shown in Figure 2. A throttle valve was installed between the APG outlet and the APC primary diluter inlet. The valve was adjusted to simulate operation of the APC representative of E31 test, where the APC is connected at the outlet of the E31 sampling line.

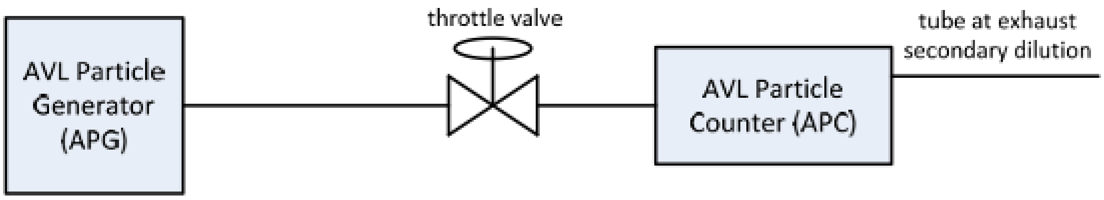

Figure 2: Experimental setup.

Recordings were taken of all the basic APC operational parameters with and without the tube at the Exhaust Secondary Dilution, for the two different DFs. Average values were calculated for the examined operational characteristics (pressures, concentrations) for the two different stages: with and without any tube connected at the exhaust secondary dilution.

The barometric (absolute) pressure recorder by the APC during the measurement was ~885 mbar, constant, while the ambient pressure without the flow restriction was at ~950 mbar. This lower pressure was achieved closing gradually the throttle valve at APC inlet.

3 RESULTS AND DISCUSSION

3.1 Effect of short tube

Figure 3 presents the schematic diagram of APC [2]. The pressure in the diluted exhaust line is measured with a pressure sensor (Diluted Relative Pressure). Connecting any tube at the Exhaust Secondary Dilution, this pressure is expected to change (increase), due to the extra pressure drop employed by the external tube.

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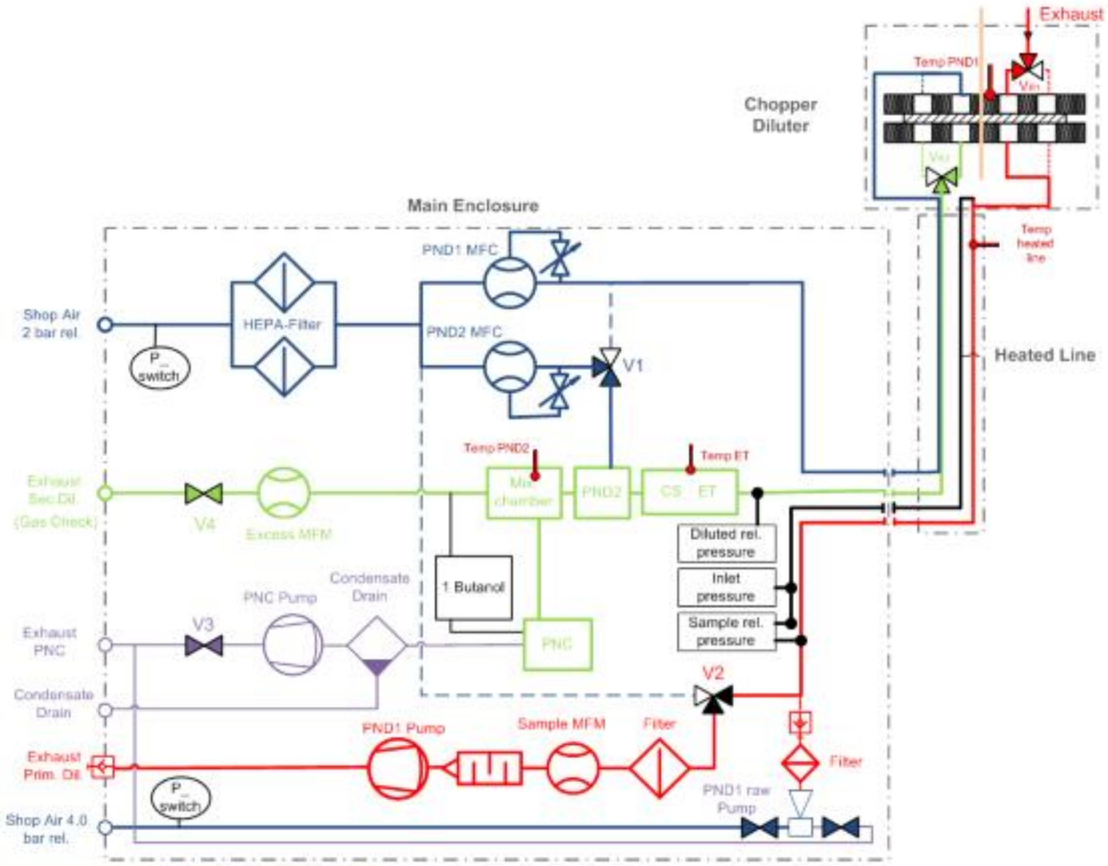

Figure 3: Schematic diagram of APC.

Figure 4 presents the schematic diagram of the CPC TSI 3792E [3]. The pressure sensors are shown, monitoring the CPC inlet pressure and the pressure difference across the nozzle and orifice.

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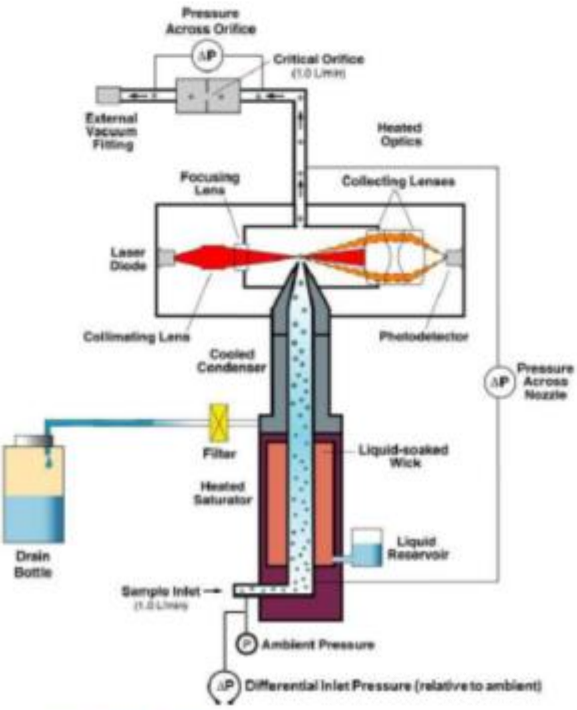

Figure 4: Schematic diagram of CPC TSI 3792E.

Figure 5 presents the effect of the tube on the APC's Diluted Relative Pressure. The concentration measured by the CPC (normalized on standard conditions) is also shown. At high DF=2020 (Figure 5b) the pressure increases by 3.9% (1.5 mbar), while for the low flow rate DF=178 (Figure 5a), it increases again by 3.9% (0.8 mbar). These values are validated by the online calculation of the pressure drop of the specific flows along the external connected tube [4], shown in Figure 6.

The two specific DFs that were selected give different diluted exhaust flow characteristics inside the APC: for the low DF (178) the diluted exhaust flow is ~9 l/min while the high DF operates at 14 l/min. Consequently, it is expected that different pressure drop is imposed when the same tube is connected at the Exhaust Sec Dil., for the two specific DFs examined.

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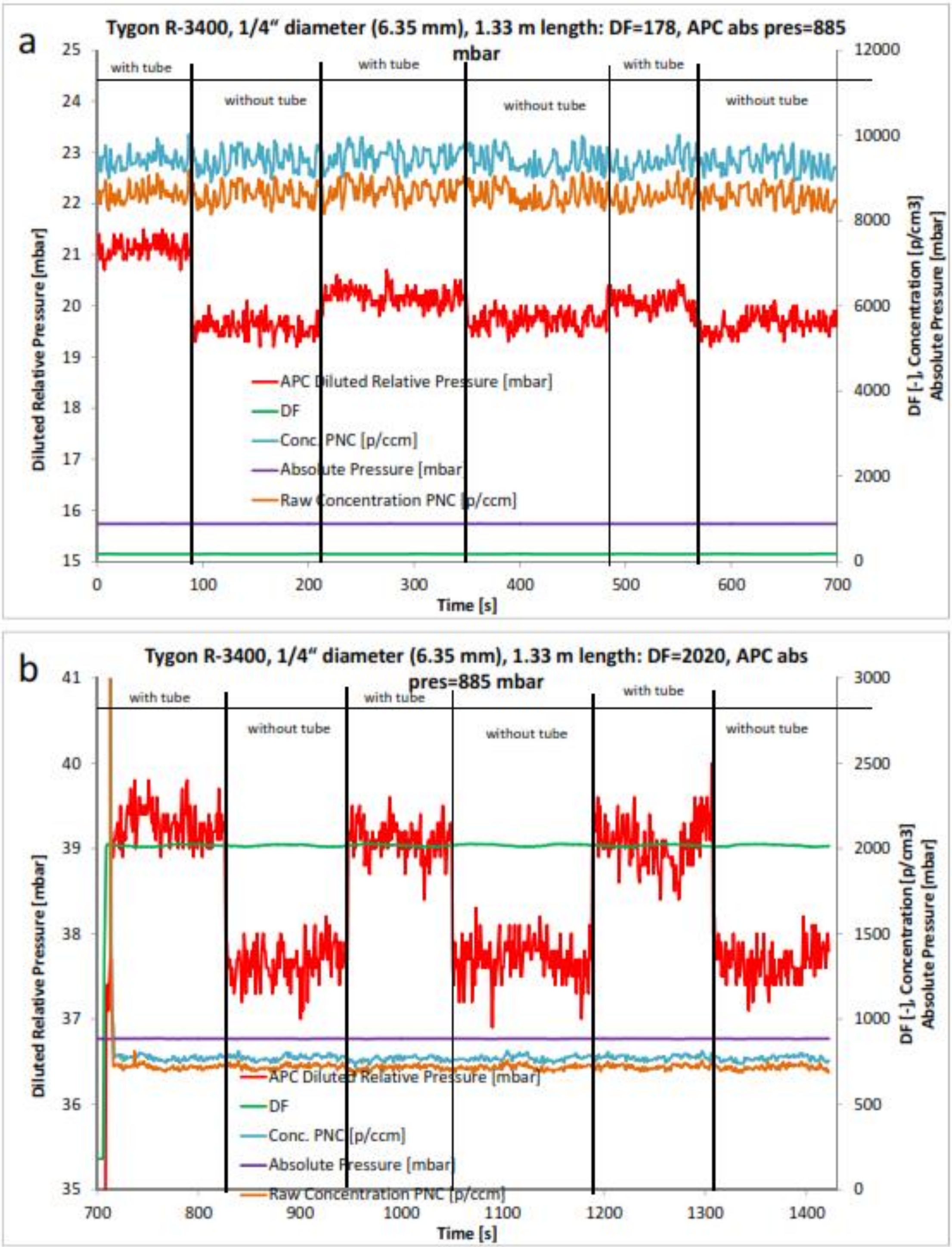

Figure 5: Effect of short tube on the APCs Diluted Relative Pressure and Normalized/Raw Concentration for (a): DF=178 and (b): DF=2020.

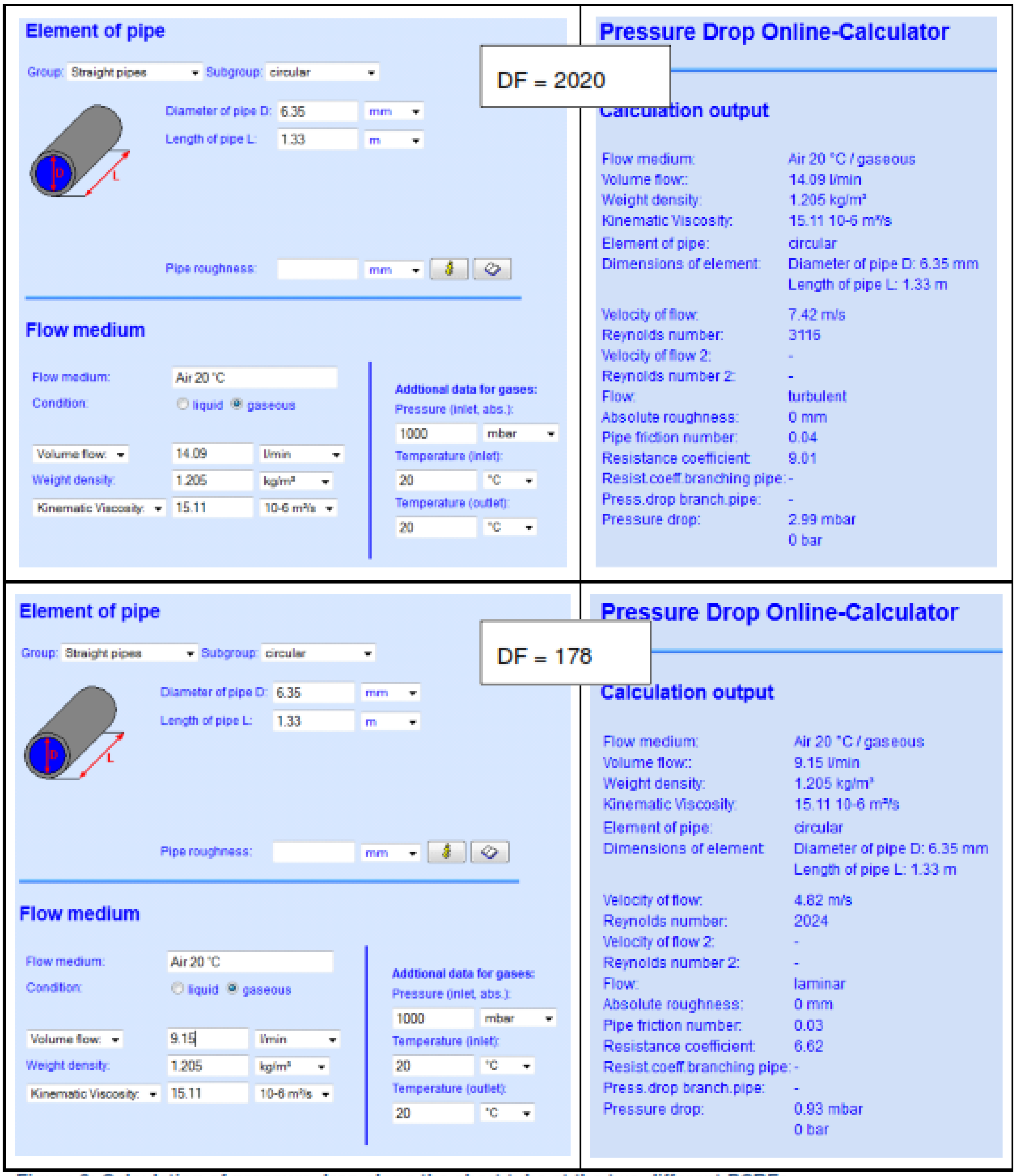

Figure 6: Calculation of pressure drop along the short tube at the two different PCRFs.

Table 1 and Table 2 show an overview of the results for the short tube for DF = 178 and 2020 respectively. The deviation of the pressures measured by the CPC were also calculated, as well as the (normalized) concentration deviation, measured by the CPC. The particle concentration was affected by 0.1% and -0.1% for DF = 178 and 2020 respectively.

Table 1: Effect of short tube on CPC concentration and pressures for DF = 178.

DF=178	Normalized concentration [p/cm^3] (Conc PNC)	Raw conc [p/cm^3]	DF [-]	Inlet Pressure PNC [mbar]	Pressure Flow Orifice PNC [mbar]	Pressure Nozzle PNC [mbar]	Diluted Relative Pressure [mbar]
With tube (average)	9391.7	8612.5	178.2	999.3	614.5	6.2	20.4
Without tube (average)	9397.3	8606.1	178.0	998.5	613.6	6.2	19.7
Percentage deviation [%]	-0.1	0.1	0.1	0.1	0.1	0.0	3.9
Absolute deviation (with-without)	-5.5	6.4	0.2	0.8	0.9	0.0	0.8

Table 2: Effect of short tube on CPC concentration and pressures for PCRF = 2020.

DF=2020	Normalized concentration [p/cm^3] (Conc PNC)	Raw conc [p/cm^3]	DF [-]	Inlet Pressure PNC [mbar]	Pressure Flow Orifice PNC [mbar]	Pressure Nozzle PNC [mbar]	Diluted Relative Pressure [mbar]
With tube (average)	770.8	717.1	2018.2	1015.0	630.1	6.3	39.1
Without tube (average)	770.0	716.7	2019.3	1015.0	628.8	6.3	37.7
Percentage deviation [%]	0.1	0.1	-0.1	0.0	0.2	0.0	3.9

Absolute deviation (with-without)	0.8	0.5	-1.0	0.0	1.3	0.0	1.5

3.2 Effect of long tube

Figure 7 presents the effect of the long tube on the APC's Diluted Relative Pressure. The concentration measured by the CPC (normalized on standard conditions) is also shown. At high DF=2020 (Figure 7b) the pressure increases by 110.7% (41.8 mbar), while for the low flow rate DF=176 (Figure 7a) it increases by 100% (19 mbar). These values are validated by the online calculation of the pressure drop for the specific flows along the external connected tube [4], shown in Figure 8.

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Austria
www.avl.com

Technical Memo 28 May 2014: report on experiments showing the immunity of APC to downstream pressure variations

Christos Dardiotis AVL/AT, William Silvis AVL/US

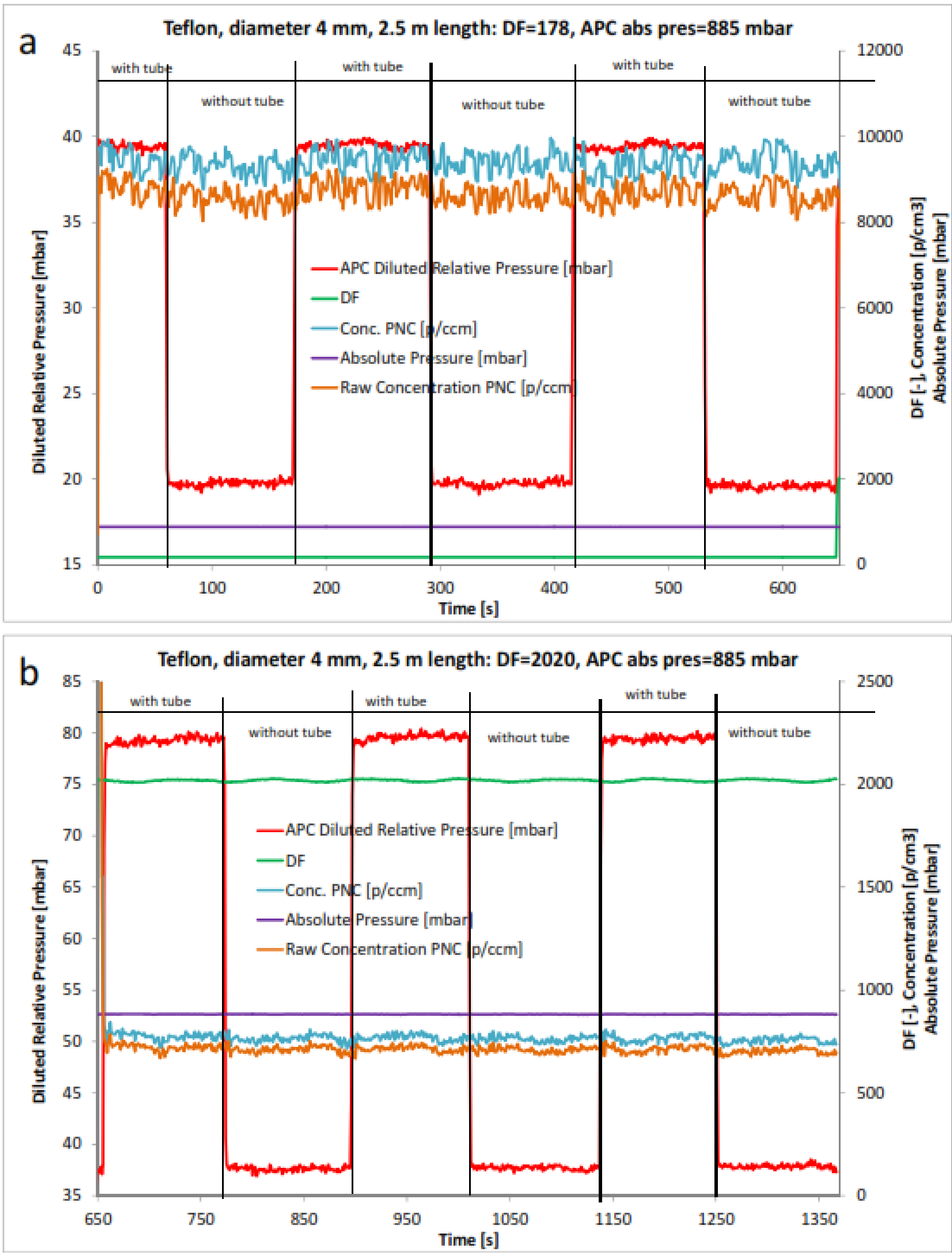

Figure 7: Effect of long tube on the APCs Diluted Relative Pressure and Normalized/Raw Concentration for (a): DF=178 and (b): DF=2020.

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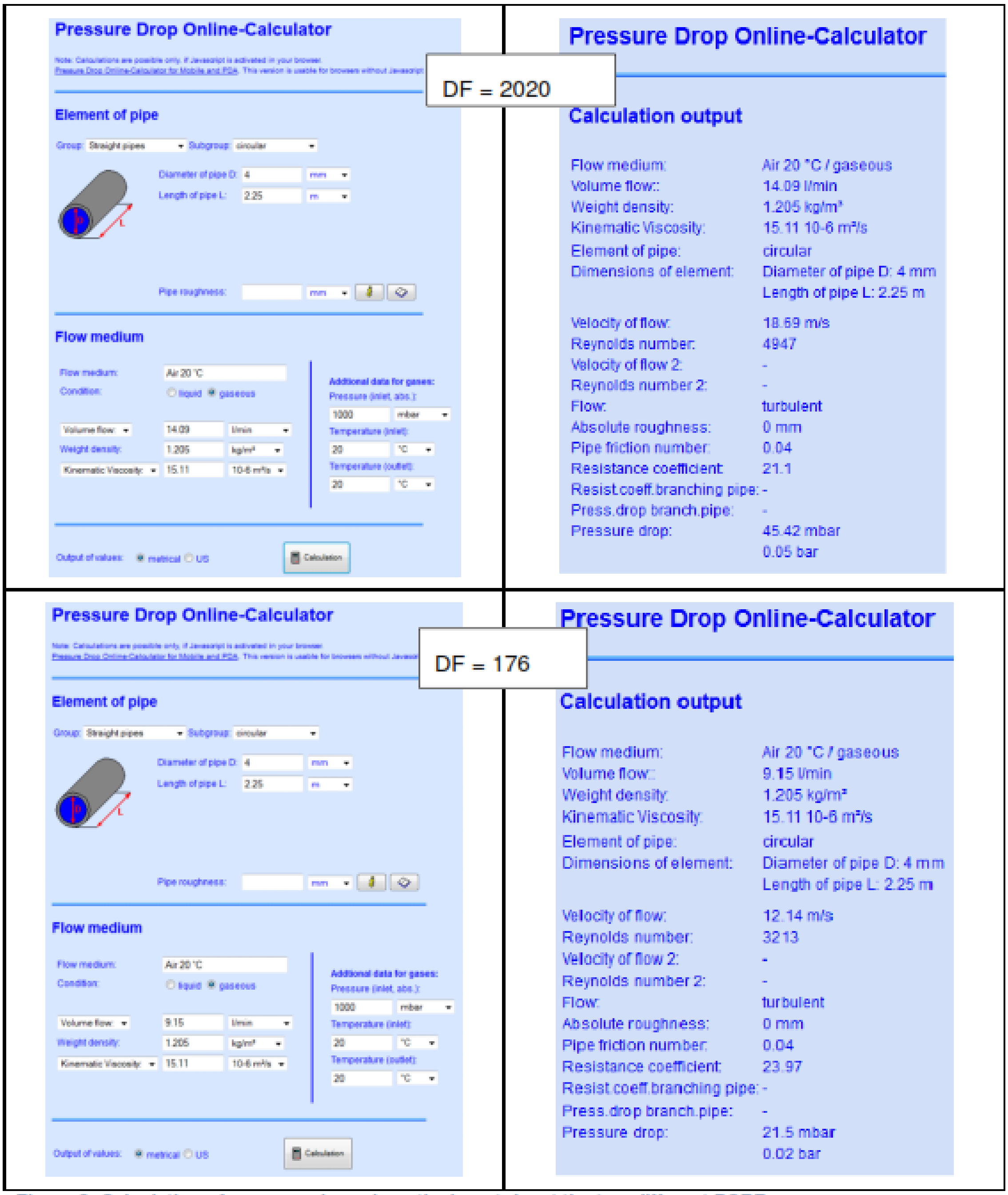

Figure 8: Calculation of pressure drop along the long tube at the two different PCRFs.

Table 3 and Table 4 show an overview of the results for the long tube for DF=178 and 2020 respectively. The deviation of the pressures measured by the CPC were also calculated, as well as the normalized concentration deviation. The particle concentration was affected by +0.1% and 0.9% for DF=178 and 2020 respectively.

Table 3: Effect of long tube on CPC concentration and pressures for PCRF = 178.

DF=178	Normalized concentration [p/cm^3] (Conc PNC)	Raw conc [p/cm^3]	DF [-]	Inlet Pressure PNC [mbar]	Pressure Flow Orifice PNC [mbar]	Pressure Nozzle PNC [mbar]	Diluted Relative Pressure [mbar]
With tube (average)	9382.5	8730.5	176.2	1015.0	630.1	6.3	39.4
Without tube (average)	9372.4	8583.9	176.1	998.9	613.4	6.2	19.7
Percentage deviation [%]	0.1	1.7	0.0	1.6	2.7	1.6	100.3
Absolute deviation (with-without)	10.1	146.6	0.1	16.1	16.7	0.1	19.7

Table 4: Effect of long tube on CPC concentration and pressures for DF = 2020.

DF=2020	Normalized concentration [p/cm^3] (Conc PNC)	Raw conc [p/cm^3]	DF [-]	Inlet Pressure PNC [mbar]	Pressure Flow Orifice PNC [mbar]	Pressure Nozzle PNC [mbar]	Diluted Relative Pressure [mbar]
With tube (average)	769.3	715.5	2019.1	1015.0	664.5	6.5	79.5
Without tube (average)	762.5	709.1	2019.3	1015.0	628.4	6.3	37.7
Percentage deviation	0.9	0.9	0.0	0.0	5.7	3.2	110.7

[%]							
Absolute deviation (with-without)	6.8	6.4	-0.1	0.0	36.0	0.2	41.8

4 OVERVIEW - CONCLUSIONS

An E31 compliant APC was investigated, regarding whether any tube connected at the Exhaust Secondary Dilution affects the CPC particle concentration. The tests were conducted under E31 representative conditions at APC inlet (Absolute pressure 885 mbar). Two different tubes were connected and investigated:

- Tygon R-3400, 1/4" diameter (6.35 mm), 1.33 m length
- Teflon, 4 mm diameter, 2.25 m length

Pressure increase was measured (and computationally validated) in the APC dilution line, due to the external tube's imposed pressure drop.

Connecting the tubes, the CPC Raw concentration was affected by max +1.7%

The CPC Normalized concentration (corrected to standard conditions, used by AIR6241 to calculate the PN engine emissions) was affected by max 0.9%.

Pressure APC differences are not associated with such proportionally high concentration changes, when a tube is connected – disconnected from "exhaust sec. dil."

It was not possible to reproduce the Raw CPC concentration deviation (+7%), reported at the previous E31 annual meeting (Dec 2013), neither by AVL (W. Silvis, C. Dardiotis), nor by Rolls-Royce (M. Johnson).

Such high concentration gaps could be attributed to other reason (still unknown), but not to the geometry of the APC outlet.

Based on relative test results conducted without any throttle restriction at the inlet of APC (Absolute pressure 950 mbar, tests not reported in this report), the APC inlet pressure does not affect the deviation of the CPC concentration measured with / without the tube connected at the exhaust secondary dilution excess flow outlet.

LIST OF SPECIAL TERMS AND ABBREVIATIONS

APC	AVL Particle Counter
APG	AVL Particle Generator
CPC (PNC)	Condensation Particle Counter (Particle Number Counter)
DF	Dilution Factor
PCRF	Particle Concentration Reduction Factor

REFERENCES

[1] AVL Particle Generator, Product Guide, AT4527E, Rev. 02, 06/2013, AVL List GmbH, Graz – Austria

[2] AVL Particle Counter, Product Guide, AT5686, Rev. 01, 12/2013, AVL List GmbH, Graz – Austria.

[3] Engine Axhaust Condensation Particle Counter, Model 3792E, Operation and Service Manual, P/N 6006470, Revision A, September 2013, TSI

[4] http://www.pressure-drop.com/Online-Calculator/

EASA
European Aviation Safety Agency

European Aviation Safety Agency

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