EUROPEAN AVIATION SAFETY AGENCY
AGENCE EUROPÉENNE DE LA SÉCURITÉ AÉRIENNE
EUROPÄISCHE AGENTUR FÜR FLUGSICHERHEIT

Research project EASA.2010/FC10 SC.01

# Studying, sAmpling and Measuring of aircraft ParticuLate Emissions III – Specific Contract 01 (SAMPLE III – SC.01)

23 October 2011

easa.europa.eu

EASA.2010.FC.10
Specific Contract N°: SC01

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

21st October 2011


**Lead Authors:**
A Crayford[2] & M Johnson[1]

**Report Authors:**

R Marsh[2], Y Sevcenco[2], D Walters[2], P Williams[3], S Christie[4], W Chung[5], A Petzold[6], A Ibrahim[6], D Delhaye[7], P Quincey[8] ,P Bowen[2] , H Coe[3], D Raper[4], C Wilson[5]

1. Rolls-Royce plc, Derby DE24 8BJ, UK
2. GTRC, Cardiff University, School of Engineering, Cardiff, CF24 3AA, UK
3. Centre for Atmospheric Science, University of Manchester, M13 NPL, UK
4. Centre for Air Transport and the Environment, Manchester Metropolitan University M1 5GD, UK
5. LCCC, The University of Sheffield, Department of Mechanical Engineering, Sheffield, UK
6. Institute of Atmospheric Physics, DLR Oberpfaffenhofen, 82234 Wessling, Germany
7. ONERA, 92320, Chatillon, France
8. National Physical Laboratory, Teddington, UK

# Table of Contents


## 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.***



***Persons wishing to reproduce in whole or in part the contents of this study are invited to submit a written request to the following address:***

**European Aviation Safety Agency**
**Postfach 101253**
**D-50452 Köln**
**Germany**

## Acknowledgements

The consortium wish to express their gratitude to a number of people, without their valued input this study would not have been as comprehensive. Particular appreciation is offered to Dr Hu Li of the Facility of Engineering, University of Leeds for adding supplemental particle size measurements and data analysis used in this report. It is also recognised that significant contributions of practical knowledge and the supply of the volatile particle removal systems used in this study were provided by Dr Jacob Swanson of the University of Minnesota United States, Dr Barouch Giechaskiel of AVL Graz, Austria, Erkki Lamminen of Dekati, Tampere, Finland and Frank Tettich of Grimm, Ainring, Germany.

## 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°: **SC01** Implementing Framework Contract N°: **EASA.2010.FC10**. The objective of this specific contract is the design and manufacture of a sampling system for measurement of particulate matter at the exhaust of large-scale gas turbine aircraft engines in support of the development of a non-volatile particulate matter (PM) certification requirement. The purpose is to test the feasibility of using a defined sampling system to reinforce the robustness of PM emissions measurements.

In order to deliver the aforementioned objective it was necessary to perform the following tasks namely;

- Characterisation of Volatile Particle Removers (VPR) efficiency;
- Design and manufacture of a defined sampling system able to measure PM mass and number;
- Full-scale gas turbine engine non-certification testing and where possible the inclusion of certification engine testing
- Uncertainty analysis of the sampling system design

To deliver the above tasks numerous experimental and desk based studies were performed which are detailed below.

- Laboratory tests of commercially available and bespoke custom made VPR based on the Particulate Measurement Programmes (PMP) guidelines.
- Combustor Rig tests employing the HES facility which has been previously shown to generate representative PM and gaseous emissions, located at the Gas Turbine Research Centre (GTRC) at Cardiff University.
- Full-scale gas turbine tests employing Sheffield University's Rolls-Royce Artouste APU.
- Desk based study investigating feasibility of utilising gas turbine maintenance facilities to conduct cost effective PM studies in order to assess SAE E31 Committee approved sampling systems.
- Desk based study investigating the penetration efficiency and uncertainty attributed with the current proposed sampling system utilising current data along with data specifically taken for this purpose collected during the aforementioned full-scale gas turbine test.

The data collected for this study allowed conclusions to be made on the effectiveness of commercially available PMP approach VPR for use in gas turbine PM measurements. The experimental programmes have also demonstrated the functionality of and added data in the calculation of associated uncertainty of measuring non-volatile aero derived PM emissions in terms of mass and number utilising the proposed sampling system. Preliminary studies have also demonstrated the potential for cost effective PM measurement campaigns on full-scale aero gas turbines at a number of sites across Europe.

***Key Results from this study include:***

1. As expected the PMP approved commercially available VPR (Dekati DEED, AVL APC400) as well as the bespoke consortium designed conform to PMP protocol in terms of laboratory based testing.
2. It was found that PMP VPR do not 'remove' all of the volatile PM but shrink over 99% of the volatile PM to a size below the 23nm cut off selected by PMP. This could lead to large uncertainties particularly if the volatile to non-volatile PM number ratio is high.
3. Catalytic Stripper technology appeared to completely remove tetracontane and lubrication oil in the form of pure volatile PM and volatile coated carbon particles and would pass PMP VPR performance specifications although it does not conform to PMP design specification.
4. Data suggests that PMP type diluters could be 'slightly' modified to potentially reduce the attainable lower size cut-off by increasing the primary dilution temperature along with the evaporation tube temperature.
5. It was witnessed during numerous combustor and full scale engine tests that volatile particles appear to exist throughout the measureable PM size range, and are not only present in the primary nucleation mode peak as current scientific understanding would suggest.
6. Online non-volatile PM mass measuring instruments (MAAP & LII) are insensitive to PMP approach pure tetracontane volatiles at loadings representative of modern large scale gas turbine engines (as witnessed in SAMPLE II Rolls-Royce full-scale engine test).
7. Analysis has shown that a reduction in uncertainty could be gained by not using a PMP type PCRF which includes the preset dilution ratio, but by including an online gaseous measurement to calculate the actual dilution ratio witnessed during testing which has been shown to be sensitive to fluctuation in sample line pressure.
8. A sampling system meeting current specifications laid out by the SAE E31 Committee has been designed and built and performed suitably for use in testing a full scale APU engine.
9. Performance specifications for specific components of future standardised sampling systems have been proposed by the consortium but have not been currently ratified by the SAE E31 Committee at present.
10. Measured penetration data provides evidence that the transport efficiency of the consortium built (SAE E31 Committee approved) proposed sampling system can be approximated to theoretical calculations for the long 25m PTFE heated line and that as long as the sampling system is kept within 1.5m downstream of the cyclone outlet the additional particle losses are negligible.
11. In principle, there are a considerable number of opportunities for in-service non-certification engine testing across Europe.
12. In general, individual maintenance facilities largely specialise in a small number of specific engine types. To obtain data that is representative of the in-service fleet will require measurements at multiple sites.
13. There is already a fully commissioned sampling probe and line at SR Technics (Zurich). Thus this offers the immediate feasibility of conducting SAE E31 Committee approved concept demonstration measurements (instrument inter-comparison, VPR assessment, SAE E31 Committee approved sampling line functionality etc.) on a limited number of engine types.

14. The provisional combined uncertainty for the non-volatile number concentration measurement (assuming 23nm cut-off), is approximately 17%.
15. There are a number of undetermined specifications of which the largest and most significant is expected to be the uncertainty associated with the currently unspecified lower size cut-off.
16. The largest components of uncertainty for non-volatile number in terms of system hardware derive from the calibration of the CPC and the lack of correction for sample line losses particularly through the non standardised Annex 16 collection section (1PTS & 2PTS).
17. For non-volatile number measurement if dilution ratios >150:1 are utilised the provisional uncertainty could increase to 19%.
18. If dilution ratios are not measured online the provisional uncertainty will increase to 20% for 150:1 dilution ratios and will further increase to 22% if higher dilution ratios are utilised (with the PMP protocol).
19. The corresponding combined uncertainty figure for the non-volatile mass concentration measurement is around 10%. However, there are currently a number of undetermined uncertainties, which are expected to increase the overall figure significantly.

***Main recommendations from this study include:***

1. If PMP type VPR methodology is to be considered then modification may be required to reduce the 23nm lower cut point.
2. Catalytic Stripper technology should be considered for integration within a dilution VPR even though they are not currently commercially available. Use of CS technology supports the possibility of a sub 23nm lower cut point. Dilution will always be required with CS technology to bring CPC measurement into single count mode
3. Further experimental work on full scale gas turbines is required to quantify the uncertainty on both non-volatile mass and number measurement systems.
4. In order to provide uncertainty evidence of volatile removal via a VPR, long (hours) OC/EC filter sampling times are required on gas turbine exhaust. Data can, and should, be obtained over a variety of engine conditions.
5. Theoretical penetration calculations can be used with confidence to provide overall sampling system performance specifications for aged (>1second residence time) exhaust. However, a separate independent study should be performed to verify the confidence level as previous experimental studies (Sevcenco 2010) showed discrepancies when comparing non-aged (raw) exhaust to theoretical penetration calculations.
6. The lower size cut-off limit is critical to the measurement uncertainty, more size distribution data across a large variety of engine types and sizes is required to ascertain where the cut-off limit should be.
7. Multiple successful demonstrations of the SAE E31 Committee sampling concept system on full-scale engine tests indicate that the concept is ready for full independent system inter-comparison verifications. Planned tests should include robustness, operability and repeatability. Wherever possible, inter-comparison measurements should be obtained simultaneously from gas turbine exhaust.

8. Further work will be required to define a specification suitable for volatile particle removal efficiency for use in aero type exhausts as it is felt the current PMP approach may not provide low enough uncertainties.
9. A cyclone performance study is required to define the required specifications which will then address the measurement uncertainty issues.

## 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 building a new methodology for the measurement of aircraft Particulate Matter (PM) emissions. Although the report does not provide a finalised 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 in this report are:

- The determination of volatile particle removal efficiency of multiple sized (15, 30, 50 & 100nm) mono-dispersed 'pure' Tetracontane ($C_{40}$) particles utilising a custom built volatile particle generator of numerous 'off the shelf' and custom built, bespoke volatile particle removers including catalytic strippers.
- The measurement of the penetration efficiency using multiple sized mono-dispersed (15, 30, 50 & 100nm) solid particles including both salt and graphite based substrates of numerous 'off the shelf' and custom built, bespoke volatile particle removers including catalytic strippers.
- Investigation of removal of volatile coatings from solid graphite particles through numerous 'off the shelf' and custom built, bespoke volatile particle removers and catalytic strippers.
- Investigation of sensitivity of online mass measurement instruments (LII & MAAP) to volatile PM.
- The use of Cardiff University's HES and custom built sampling lines and exhaust conditioners to study the volatile particle removal efficiency of numerous 'off the shelf' and custom built, bespoke volatile particle removers when subjected to a simulated gas turbine exhaust.
- The design and manufacture of an SAE E31 concept sampling system for installation behind full-scale gas turbine exhausts.
- Use of Sheffield University's full-scale APU gas turbine to demonstrate the aforementioned SAE E31 concept sampling system for use in the measurement of non-volatile PM mass and number.
- The use of Sheffield University's full-scale APU gas turbine and custom built SAE E31 concept sampling system and exhaust conditioners to study the volatile particle removal efficiency of numerous 'off the shelf' and custom built, bespoke volatile

particle removers including catalytic strippers when subjected to a real gas turbine exhaust.

- The determination of penetration efficiency through the SAE E31 Committee concept sampling system, in terms of number and size distribution and comparison to theoretical models.
- Investigation into the feasibility of using maintenance and pass off test facilities for future investigation of PM emissions.
- An uncertainty appraisal of the proposed SAE E31 Committee non-volatile PM sampling system highlighting current understanding and still unknown uncertainties.

## 2. Introduction

The 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 prohibitive 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 quantity of PM. Both mass and number concentration will need to be measured in a format that can act as a standardised test under engine certification conditions. Other known problems include the accurate on-site quantification of the ratio of volatile to non-volatile PM emissions, especially aerosol precursors.

The committee on Aviation and Environmental protection (CAEP) within ICAO expects the delivery of a non-volatile PM standard requirement by the end of 2016. EASA and the other Regulatory agencies (FOCA, CAA, FAA, TC & EPA) requested the SAE E-31 to provide a ballot-ready non-volatile PM mass and number ARP by February 2013. The SAE E-31 PM sub-committee on aircraft exhaust emissions measurement has been working on improved measurement activities for aircraft non-volatile PM emissions.

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 SAMPLE I 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.

Thus there is the need to develop a concept sampling system in terms of components, manufacture and operability to standardise PM measurement, along with reliably quantifying the effects of volatile particle removers in terms of efficiency and losses in providing a non-volatile exhaust sample to the number counting instruments. 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. However, further validation in terms of practicability and robustness of a sampling system capable of delivering non-volatile PM to both mass and number measuring analysers is required in order that the SAE E31 Committee can develop an ARP for the measurement of non-volatile PM mass and number.

## 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 **SC01.**

The main purpose of this specific contract **SC01** is to apply the knowledge gained from the previous few years of study (SAMPLE & SAMPLE II) along with that shared within the SAE E31Committee gained from full-scale engine testing in order to check the practicability and robustness of a defined, designed and built sampling system.

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

Task 1: Characterisation of Volatile Particle Removers (VPR) efficiency

Task 2: Design and manufacture of a defined sampling system able to measure PM mass and number

Task 3: Full-scale gas turbine engine non-certification testing and where possible the inclusion of certification engine testing.

Task 4: An uncertainty analysis of the sampling system design

# 4. Task 1: Volatile Particulate Matter Removal Characterisation.

## 4.1 Introduction

The civil aviation regulatory bodies have expressed a wish that only non-volatile PM certification requirement will be delivered at the upcoming CAEP cycle. In order to ensure accurate, repeatable measurements are taken in terms of mass and number it will therefore be necessary to remove any volatile PM that has formed in the sampling system prior to the measurement of PM number. However, due to the insensitive nature of various mass measurement instruments to volatile PM the requirement of volatile removal should not be required prior to mass measurement. In the automotive sector within the Particulate Measurement Programme (PMP) a similar approach has been adopted for the measurement of PM number for reciprocating diesel engines across Europe, Switzerland and Japan. The programme highlighted that previous research programmes DETR/SMMT/CONCAVE showed that numerous technologies displayed the same number counts if volatile PM was included in the count which made distinguishing one technology from an inferior one problematic. However, elimination of volatile particles from the counted particles provides a more repeatable measurement and distinguishes between engine technologies by eliminating nucleation mode particles, i.e. volatile particles. Therefore, it was decided within PMP that only solid particles should be counted to distinguish between technologies.

Due to the requirement of volatile particle removal which is required for regulated engine tests within the PMP guidelines, there are numerous commercially available Volatile Particle Remover (VPR) systems which adhere to the PMP approach. Thus it was decided within the SAE E31 that it would be prudent to determine whether these already available and tested systems designed for use in the automotive sector may be applicable for use within the ARP being developed for PM measurement in the aero sector.

In order to adhere to the PMP guidelines there are a number of factors a particular VPR has to satisfy in terms of specification performance, and these factors are checked annually using a prescribed method to ensure a VPR is compliant. As such there are various designs of VPR which satisfy the PMP specification performance but they all follow a basic design of primary dilution stage followed by an evaporation tube and finally a secondary dilution stage.

However, it also needs to be observed that the PMP protocols were designed specifically for the measurement of non-volatile PM number counts behind diesel reciprocating engines fitted with a ceramic diesel particulate filter (DPF) thus may not be applicable for the provision of purely non-volatile PM when sampling exhausts from other smoke sources. For this reason there are other non PMP compliant volatile particle removers/ diluters on the market which were highlighted during SAE E31discussions such as the Grimm Emission Sampling System.

There are also other methods being researched and developed to remove volatile species from exhaust products based on the use of heated catalysts. As recent discussions within the SAE E31 highlighted these techniques have potential for use in the measurement of non-volatile PM from large-scale aero gas turbine exhausts it was decided that inclusion of this technology into this remit of work would be beneficial. However, at present catalytic strippers (CS) are research tools that are not yet commercially available thus a bespoke CS was sourced from the University of Minnesota and trialled.

The VPR designs tested in this study can be broadly characterised into 4 concepts based on the method and/or types of diluter employed namely:-

- Rotating – as utilised by the manufacturers AVL
- Eductor – as utilised by Dekati and also as used in 'bespoke' custom consortium VPR
- Mass flow recirculation - as utilised by Grimm
- Catalytic - as developed by University of Minnesota

In order to appraise the functionality and effectiveness of each type of VPR it was decided that there was the requirement for multiple tests using different sources of PM thus Task 1 was conducted utilising laboratory, combustion rigs and full scale engine tests the details of which are discussed further below.

## 4.2 Details of Volatile Particle Removers

As discussed above there are various ways of constructing a VPR. Thus, PMP gives a detailed description of the design and function of a PMP approved VPR as follows:

Description: *The VPR shall comprise one particle number diluter (PND1), an evaporation tube and a second diluter (PND2) in series. This dilution function is to reduce the number concentration of the sample entering the particle concentration measurement unit to less than the upper threshold of the single particle count mode of the CPC and to suppress nucleation within the sample.*

Specification: *The VPR shall achieve >99.0 % vaporisation of 30 nm tetracontane ($CH_3(CH_2)38CH_3$) particles, with an inlet concentration of >10,000 $cm^{-3}$, by means of heating and reduction of partial pressures of the tetracontane. It shall also achieve a particle concentration reduction factor ($f_r$) for particles of 30 nm and 50 nm electrical mobility diameters, that is no more than 30 % and 20 % respectively higher, and no more than 5 % lower than that for particles of 100 nm electrical mobility diameter for the VPR as a whole.*

To achieve the above PMP prescribes the method by which a VPR is to function as set out by Figure 1.

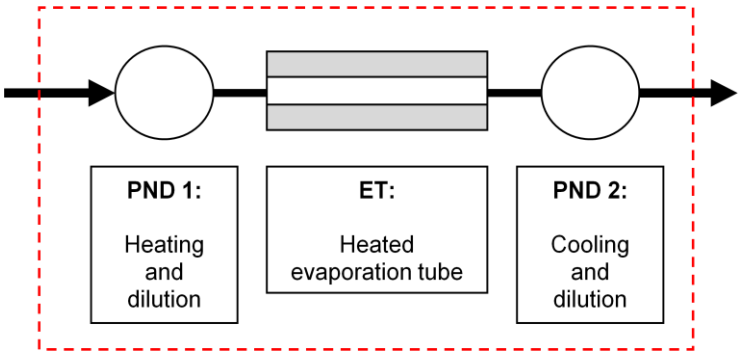


**Figure 1 Schematic of PMP prescribed VPR**

As can be seen a PMP prescribed VPR consists of three components; a primary diluter (PND 1) which must heat the sample to a temperature of 150°C to 400°C and dilute the exhaust by more than 10:1 and less than 200:1 this reduces the particle number concentration, so that agglomerations and particle deposits are largely prevented whilst starting evaporation of volatile PM and preventing condensation. The diluted sample then passes into a heated evaporation tube (ET) which further heats the sample to between 300°C to 400°C in order to drive all volatile PM into the gas phase. There is then finally a secondary dilution stage (PND 2) which further dilutes the sample by between 10:1 and 15:1 to ensure there is no re-condensation of the volatile vapour whilst also reducing the temperature to below 35°C. The final dilution stage is also used to lower number concentrations to an acceptable level for entry to the condensate particle counter (CPC) whereby counting is only permissible in single count mode to remove the higher uncertainty associated with photo-metric count mode.

Within PMP the CPC specified has a $D_{50}$ of 23nm this was a pragmatic lower cut-off adopted to include as much solid carbonaceous PM as possible whilst not measuring shrunk volatile PM and metal oxides fuel additives (10-15nm). The 23nm cut-off was thus chosen as this was the smallest cut-point above 17nm that could be commercially built with a suitably sharp efficiency curve. Therefore a PMP approved VPR only has to 'shrink' volatile PM to a diameter of less than 23nm in order for the sample to appear that it contains only non-volatile PM. Thus an acceptable PMP VPR exhaust does not ensure that there is no volatile PM just that there is little volatile PM with a diameter of >23nm.

As discussed earlier it was decided that a commercially available VPR of each of the 4 generic types should be tested. For this reason an AVL Particle Counter (APC400), Dekati Engine Exhaust Diluter (DEED), Grimm Emission Sampling System (ESS) , bespoke custom made consortium designed VPR and a University of Minnesota Catalytic Stripper were tested details of each is given below.

### 4.2.1 AVL Particle Counter (APC)

The AVL Particle Counter complies with all PMP VPR requirements and adheres to UNECE R83. Full details of the instrument can be found in the AVL product description literature however, a brief description is given below:

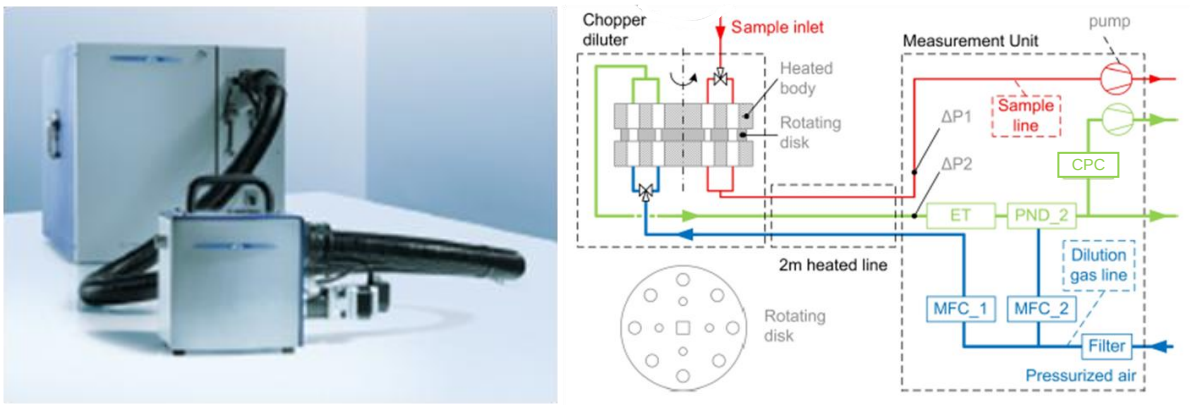


**Figure 2 Photograph and schematic of AVL Particle Counter**

The AVL system presented as a photograph and schematic in Figure 2 works on the basis that a pump draws the exhaust gas into the system where the sampled exhaust gas is then diluted in the primary patented rotary "Chopper Diluter" with cleaned hot air at a temperature of 150°C. After the hot primary dilution, the diluted exhaust passes along a 2m flexible sample line to the main unit where the diluted sample is further heated up to a temperature of 300°C to 400°C in the evaporation tube. Afterwards, a secondary dilution is performed by a mass flow controlled diluter supplying cool highly diluted sample to the integrated CPC (TSI 3790) with a size range of 23nm to 2.5µm according to UNECE-R83 specifications.

The AVL particle counter has Ethernet connected control software which affords the user real time number concentration readings along with numerous set point control of dilution ratio between 100 and 2500:1 which enables the user to keep the CPC within single count mode.

### 4.2.2 DEKATI Engine Exhaust Diluter (DEED)

The Dekati DEED complies with all PMP VPR design requirements and adheres to UNECE R83, and was used as the VPR in the PMP golden system. Full details of the product can be found in Dekati instrument literature however an overview is given below.

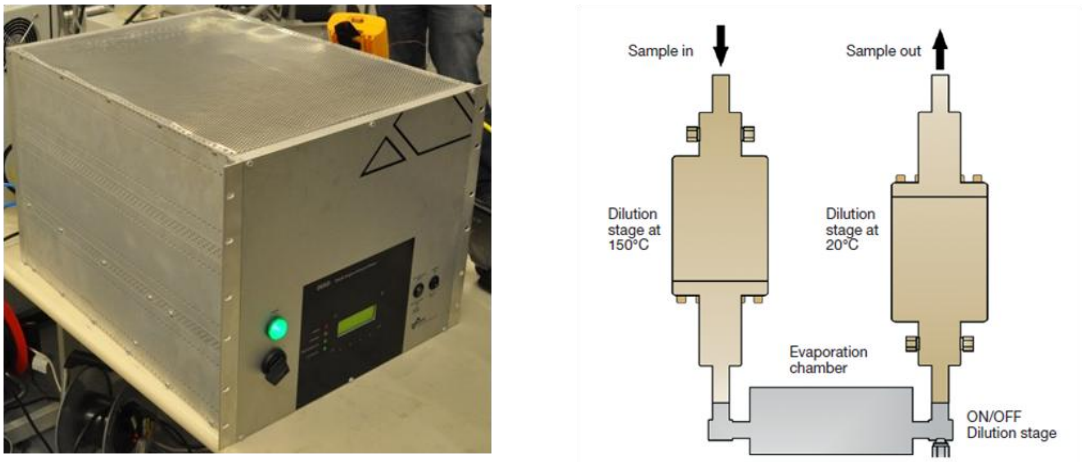


**Figure 3 Photograph and schematic of Dekati Engine Emission Diluter (DEED)**

The DEED is depicted as a photograph and schematically in Figure 3. It is observed that Dekati ejector diluters are used as both the primary and secondary diluters and that the sample enters a primary diluter whereby it is diluted at approximately 10:1 at a temperature of 150°C it then enters an evaporation tube which can be operated between 300°C-400°C before entering the secondary diluter where it is diluted a further 10:1 at 20°C. Thus the DEED gives an overall dilution ratio of 100:1 in normal operation however; the user can select to add an extra stage of dilution after the evaporation tube which gives the user the option of an overall dilution ratio of 1000:1

As can be seen the DEED is fully constructed in stainless steel with no moving parts so is of a robust design. It has a very easy front panel operation not requiring trained personnel to run the kit. However, the DEED does not contain a CPC so this has to be added thus post processing of number would be required offline.

### 4.2.3 GRIMM Emission Sampling System (ESS)

The Grimm Emission Sampling System is not based on the PMP designs as it does not incorporate a separate evaporation tube and incorporates the primary diluter into a sampling probe as shown in Figure 4.

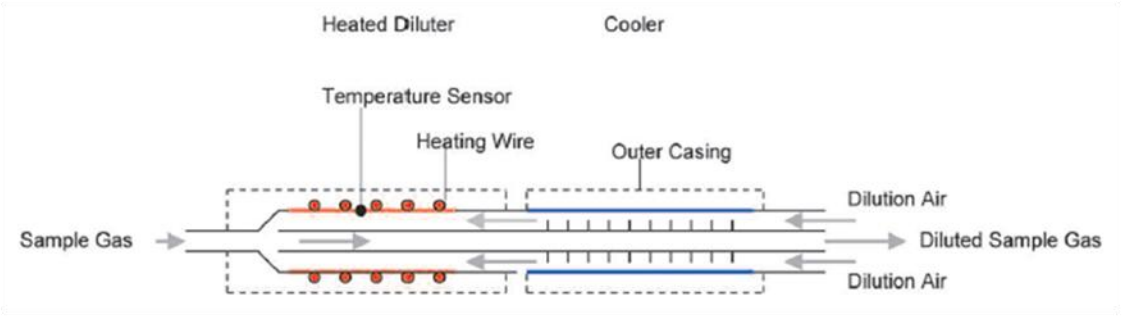


**Figure 4 Schematic of primary diluter/sampling probe used by Grimm Emission Sampling System (ESS)**

An overview of the complete Grimm ESS system is presented in the Grimm product literature but a brief description is given below and shown as a photograph and schematically in Figure 5.

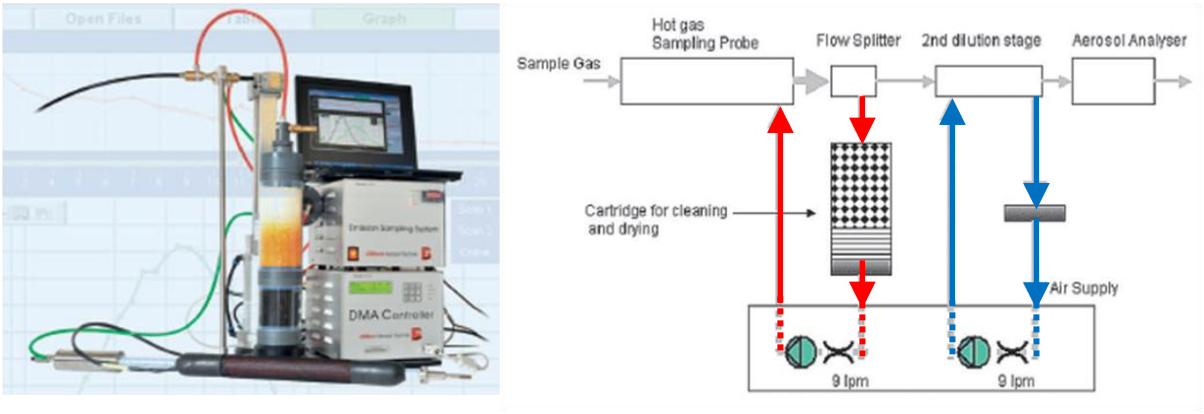


**Figure 5 Photograph and schematic of Grimm Emission Sampling System (ESS)**

As can be seen the Grimm EES contains a primary hot dilution stage contained within the sampling probe where the diluent is supplied at 9 L/min from cooled, dried & filtered exhaust which is re-circulated from a flow splitter (as highlighted by red arrows). There is then a secondary re-circulating 9 L/min loop which passes through only a filter as it is assumed the sample at this stage is dry which acts as a secondary dilution stage (as highlighted by blue arrows). The sample then passes to the Grimm SMPS for size and number counting.

The dilution ratio on the Grimm EES is determined by the flow rate requirement of the aerosol analyser as the two re-circulating loops are set at 9 L/min therefore it is stated that for a 1:100 dilution ratio 1 L/min needs to be pulled by the aerosol analyser and this would increase to 1:961 if 0.3 L/min is pulled. This also means that if greater than 10:1 dilution is required on either of the dilution stages as may be the case for aero exhaust measurement that the maximum flow that can be used for analysis is 1 L/min.

### 4.2.4 Bespoke 'Custom' Consortium VPR

The bespoke custom consortium VPR is constructed using two PALAS VKL 10E eductor diluters which have been retrofitted with high temperature Kalrez seals allowing their upper temperature to be raised to 320°C.

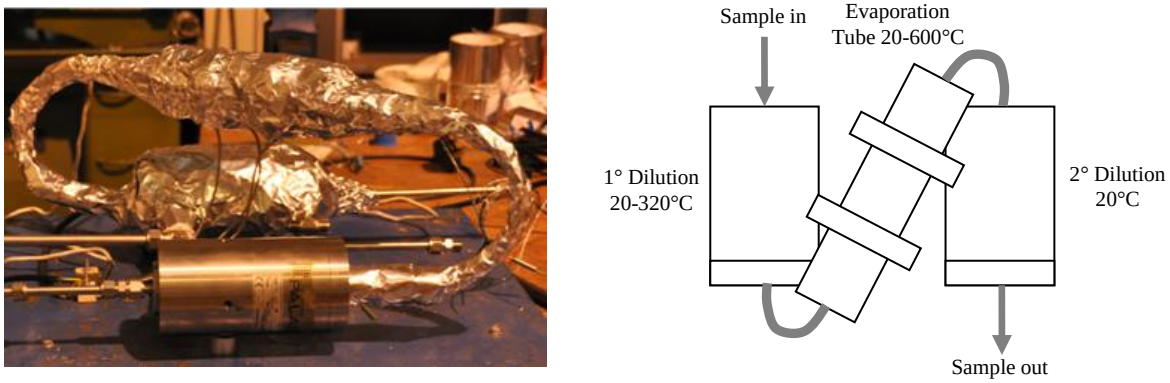


**Figure 6 Photograph and Schematic of bespoke custom consortium VPR**

The bespoke system is shown by photograph and schematically in Figure 6, it can be observed that this VPR built as a research tool and has variable temperatures of the primary diluter and evaporation tube from ambient to 320°C and 600°C respectively. The evaporation tube has been manufactured to be modular as shown below (Figure 7) affording the residence time to be varied from 0.5 to 1.0 seconds depending on whether the central section is inserted.

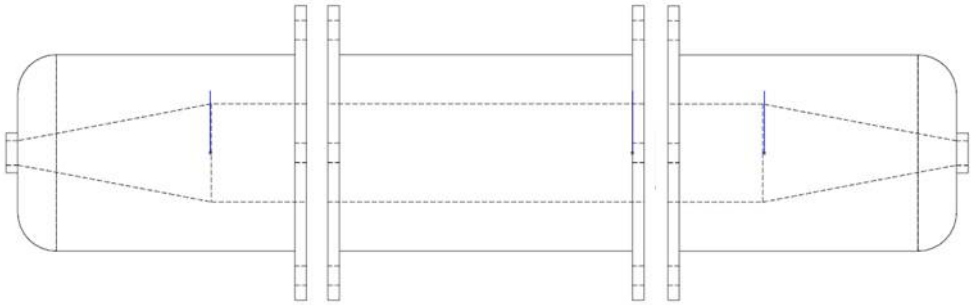

**Figure 7 Schematic of Evaporation tube of bespoke consortium VPR**

It was found that the dilution ratio of eductor diluters is sensitive to inlet, diluent and body temperature therefore control of dilution ratio had to be done manually via mass flow control and $CO_2$ measurement.

### 4.2.5 Bespoke 'Custom' University of Minnesota Catalytic Strippers

The principle of operation of the catalytic stripper (CS) is to evaporate semi-volatile particulate matter and to oxidize the resulting gas phase compounds. Inorganic compounds such as sulphate are chemically absorbed onto the 'washcoat' of the catalyst. This approach differs from other methods such as a thermal denuder and PMP type volatile particle remover (VPR) that remove gas phase material via physical adsorption or rely on dilution to prevent re-nucleation.

Due to varying flow rates being required by different analysers it was necessary to use two variants of the CS a 1.5 L/min mini CS prototype and a 10 L/min University of Minnesota Laboratory CS, photographs (Figure 8) and details of the two working units utilised in this study are presented below.

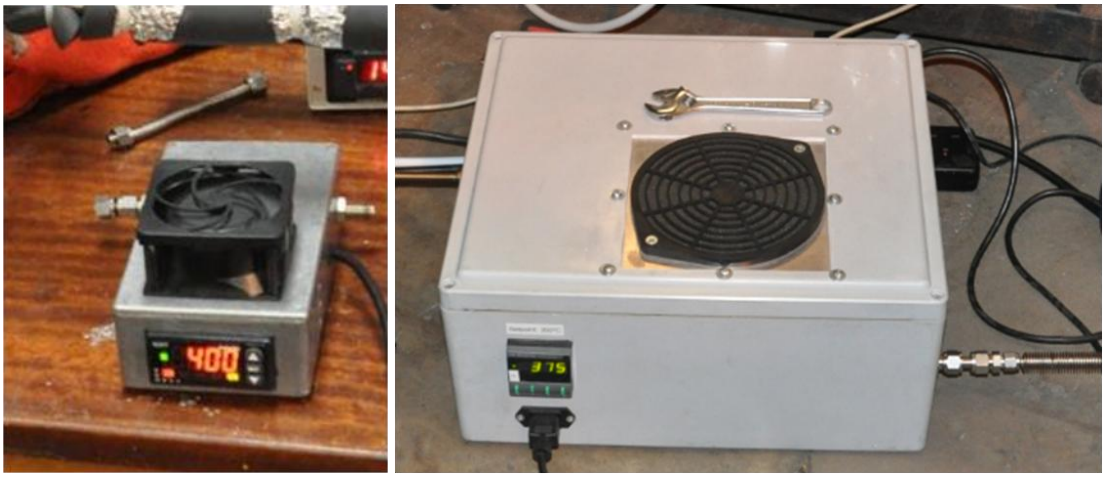

**Figure 8 Photograph of working prototype CS units with flow rates of 1.5L/min & 10L/min utilised in this study**

### *4.2.5.1 Mini Prototype 1.5 L/min Catalytic Stripper*

The 1.5 L/min Mini Catalytic Stripper Prototype (is a catalyzed ceramic substrate provided by Johnson Matthey that is designed to remove sulphur compounds by absorption and semi-volatile hydrocarbons via oxidation. In normal operation, the CS is heated to 300 – 400 °C and the aerosol flow rate through the CS is 1.5 L/min which thus makes it compatible for use with a CPC or SMPS. A photograph of the mini prototype CS core and a schematic of the principle of CS construction are presented in Figure 9.

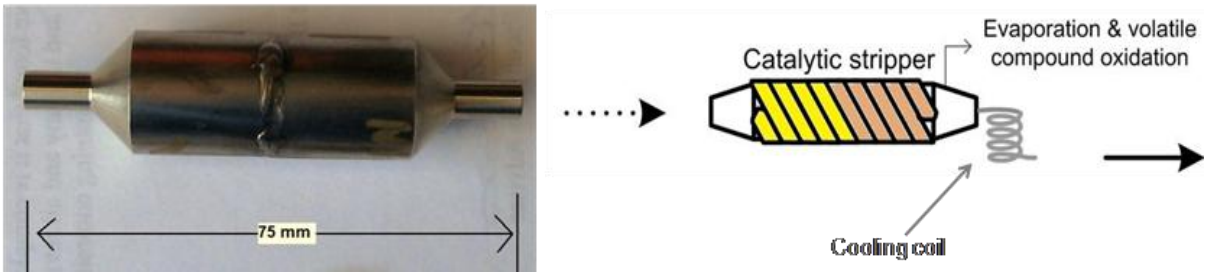


**Figure 9 Photograph of mini prototype core and schematic of CS technology**

The oxidation catalyst removes the semi-volatile hydrocarbon particles and vapours in the exhaust gas stream, which consists mainly of unburned fuel and lubrication oil.

All components in the exhaust gas containing sulphur oxides are absorbed and stored as $BaSO_4$ as shown below:

$$H_2SO_4 \rightarrow H_2O + SO_2,$$
$$SO_2 + ½\ O_2 \rightarrow SO_3,$$
$$BaO + SO_3 \rightarrow BaSO_4.$$

When the S-Trap exceeds its capacity for $BaSO_4$ storage, it is regenerated by heating at 450–500°C in nitrogen (95%) + hydrogen (5%).

The technical design specifications for the mini prototype CS are given below in Table 1.

**Table 1 Design specifications of mini 1.5 L/min Prototype University of Minnesota CS**

| | |
|---|---|
| **Core Length** | 3.8 cm |
| **Core width** | 1.7 cm |
| **Cell density** | 600 cells/in |
| **Cell wall thickness** | 2.5 mil |
| **Flow rate** | 1.5 L/min |
| **$C_{40}H_{82}$ removal** | 99.5 % |
| **50% cut off size** | 7 nm |

### *4.2.5.2 University of Minnesota Laboratory 10 L/min Catalytic Stripper*

The 10 L/min CS uses an oxidation catalyst to remove semi-volatile hydrocarbons via oxidation. The principal mechanisms by which particles are lost in the CS are thermophoresis and diffusion. Previous work documented particle losses at a variety of operating conditions including the 10 L/min and 300 °C conditions used in this study using sodium chloride aerosol and a differential mobility analyzer. Approximately 50% of 15 nm particles penetrate at this condition. Further details are available elsewhere (Stenitzer, 2003). At 300 °C and 10 L/min the CS gave essentially 100% removal of sulphate and lubricating oil particles in the 15–200 nm diameter range.

Properties of 10 L/min CS substrate are presented below in Table 2.

**Table 2 Design specifications of 10 L/min Laboratory University of Minnesota CS**

| | |
|---|---|
| **Length** | 100 mm |
| **Diameter** | 32 mm |
| **Channel dimensions** | 1,116 x 1.116 x 110 mm |
| **Channel density** | 350 channels/$in^2$ |
| **Wall thickness** | 5,5 mil |
| **Washcoat loading** | 1,223 g/$cm^3$ |
| **Washcoat density** | 1,500 g/$cm^3$ |

### 4.2.6 Summary Table of VPR Technologies Studied

**Table 3 Summary of VPR tested during this study**

| | AVL | DEKATI | GRIMM | Bespoke | Catalytic Stripper |
|---|---|---|---|---|---|
| **Operability** | Plug and play<br>Computer control required<br>Rack mountable | Plug and play<br>User Friendly – extremely simple<br>Rack mountable | Not simple to install<br>Easy to run – no computer required<br>Not rack mountable | Requires online dilution ratio measurement, needs refining | Plug and play<br>User Friendly – extremely simple<br>Not commercially available |
| **Dilution type** | Rotary | Eductor | Re-circulating mass flow | Eductor | None |
| **Specification** | 150°C Dilution<br>350°C ET<br>0.2s residence time | 150°C Dilution<br>350°C ET<br>0.4 residence time | 200°C Dilution<br>No ET | 300°C Dilution<br>400°C ET<br>1s residence time | 350°C |
| **Dilution Calibration** | Online using Nitrogen | Online using Nitrogen | Offline via flow measurement | Online using Nitrogen | Not required |

## 4.3 PMP Methods for Validation of Volatile Particle Removers

As discussed earlier the PMP protocol specifies a performance specification for numerous efficiencies which is outlined as a report (AEA Energy & Environment, ED47382004/VPR) There are numerous checks that must be conducted in respect to volatile particle removal and particle concentration reduction factor (PCRF) to validate a VPR as compliant within PMP protocols and the methods adopted for each are given in the following sections.

A general experimental setup as determined by PMP for both PCRF and volatile particle removal efficiency is given schematically as Figure 10 and the consortium based its laboratory trials on this set up.

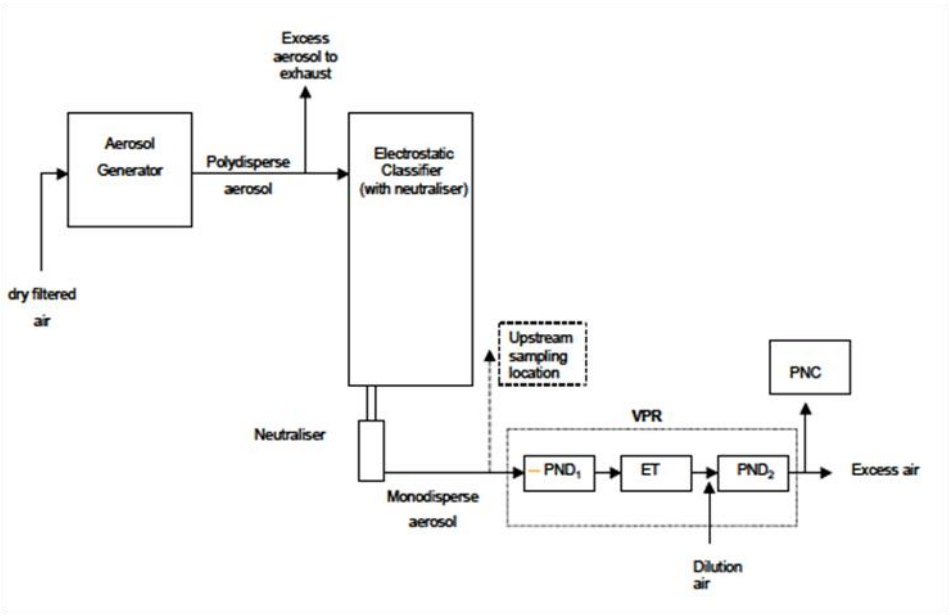


**Figure 10 PMP prescribed Calibration setup for the validation of the VPR for volatile particle removal efficiency**

However, it should be noted that the consortium is not a certified PMP test laboratory, but due diligence was applied to the experimentation and where possible all calibrations were performed to a traceable standard (*e.g.* flow, temperature, pressure, gas analysis etc. and a secondary calibration CPC transfer standard was used to validate inter CPC linearity).

As this study is ultimately concerned with the validation of VPR for use in the future SAE ARP on non-volatile PM measurement, there were sometimes educated revisions made to the prescribed PMP method based on the outcomes of SAE E31 discussions. These revisions gave extra data affording a better understanding of the applicability of a VPR technology for the measurement of non-volatile PM number from the exhaust of a modern full scale gas turbine engine.

### 4.3.1 Determination of Solid Particle Concentration Reduction Factor (PCRF)

In order to meet the prescribed PMP specification a PCRF must be calculated which is used to correct for the losses associated with solid particle penetration efficiency through the VPR. For the VPR to pass PMP the following must be conducted:

For each nominal dilution setting and particle diameter the ratio of upstream number concentration to downstream number concentration should be calculated:

The particle concentration reduction factor at each particle size ($f_r(d_i)$) shall be calculated as follows in (1);

$$f_r(d_i) = \frac{N_{in}(d_i)}{N_{out}(d_i)} \quad \textbf{(1)}$$

*Where $N_{in}$ ($d_i$) = upstream particle number concentration for particles of diameter $d_i$;*
*$N_{out}$ ($d_i$) = downstream particle number concentration for particles of diameter $d_i$; and*
*$d_i$ = particle electrical mobility diameter (30, 50 or 100 nm)*

For each nominal dilution setting the mean particle concentration reduction factor ( $\overline{f_r}$) should then be calculated for all particle diameters as given in equation (**2**);

$$\overline{f_r} = \frac{f_r(30\ nm) + f_r(50\ nm) + f_r(100\ nm)}{3} \quad (2)$$

At each nominal dilution setting the VPR shall achieve a particle concentration reduction factor ($f_r$) for particles of 30 nm and 50 nm electrical mobility diameters, that is no more than 30 % and 20 % respectively higher, and no more than 5 % lower than that for particles of 100 nm electrical mobility diameter for the VPR as a whole as shown in equations (3) & (4):

$$1.3 > \frac{f_r(30\ nm)}{f_r(100\ nm)} > 0.95 \quad (3)$$

$$1.2 > \frac{f_r(50\ nm)}{f_r(100\ nm)} > 0.95 \qquad (4)$$

For VPRs with variable primary diluter settings a minimum of five particle concentration reduction factors ($f_r$) corresponding to five nominal dilution settings are required. For VPRs with a variable secondary diluter ($PND_2$) fifteen particle concentration reduction factors ($f_r$) will be produced (five primary diluter settings at three secondary diluter settings). For VPRs with fixed dilution settings only one particle concentration reduction factor will be produced.

In order to calculate the above PCRF values PMP prescribes the method to do so in detail. Once again there are two methods for doing this either utilising one or two calibrated CPC. It was decided that a one method system be employed (however, a policeman CPC was also added upstream of the VPR to add confidence to the method.)

The method which was broadly followed by the consortium to calculate PCRF is given below as outlined by the PMP guidelines.

The particle concentration reduction factor ($f_r$) may be measured in two ways:

1. Using one particle counter. In this case the upstream and downstream particle number concentrations are recorded using the same CPC sampling at either position through equivalent sampling lines. Upstream and downstream sampling lines are simply exchanged and the number concentration allowed to stabilise before measurement commences. Finally, the upstream sampling line should be reconnected to the CPC to verify that the upstream concentration has not drifted (by more than 10 %) during the measurement.
2. Using two particle counters, one measuring upstream/at the VPR inlet and one measuring downstream/at the VPR outlet. If this option is selected then it is assumed that the correlation between the two CPCs (at the inlet and outlet of the VPR), has been confirmed before this procedure commences. The CPCs' response at all particle diameters (30, 50 and 100 nm) must be measured. Readings from one CPC must be adjusted to take into consideration any differences between the two instruments. If two different models of CPCs are used, their counting efficiency may differ significantly for 30 nm diameter particles (due to the $D_{50}$=23nm being close to the 30nm measurement point, depending on the gradient of the counting efficiency 100% counting efficiency in most analysers will not be met thus the number count witnessed for this data point will be reliant on the actual 30nm counting efficiency for each individual analyser). Additionally the data from the upstream and downstream CPCs must be time aligned to account for the VPR residence time.

Prepare the VPR and CPCs for use:

a) Position all apparatus according to the manufacturer's instructions, this will be generally similar to that described in Figure 10
b) Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (*e.g.* for rotating disc diluters remove the disc and clean using an appropriate solvent).

c) Perform any routine maintenance of the VPR as advised by the manufacturer (*e.g.* replacement of filters, tubing *etc.*).
d) Switch on the electrostatic classifier (or other source of mono-disperse particles), CPCs and VPR.
e) Fill the CPCs with working fluid and allow the saturator and condenser to reach their specified temperatures.
f) Apply an external vacuum source to the CPCs if not fitted with an internal pump.
g) Do not proceed unless all indicators on the CPCs show correct instrument status (*e.g.* temperature, liquid level, flow and laser *etc.*).
h) Check the inlet flow rates of the CPCs with an appropriate calibrated flow meter (low pressure drop variety recommended, *e.g.* bubble flow meter). The flow into the particle counter shall report a measured value within 5 percent of the particle counter nominal flow rate.
i) Check that zero concentration is reported when a HEPA filter (class H13 of EN 1822:1998 or better filtration efficiency) is attached to the inlet of the CPCs. The CPC requires attention from the manufacturer if concentrations greater than 0.2 particles $cm^{-3}$ are reported.
j) If required, apply clean dry filtered air to the VPR at pressures specified by the manufacturer.
k) Switch on heating to VPR and allow unit to reach specified temperatures.
l) Connect the CPC to the VPR.
m) When the VPR has reached its specified temperature settings connect a HEPA filter (class H13 of EN 1822:1998 or better filtration efficiency) to the inlet and ensure a zero concentration is reported on the CPC. Do not proceed if particle concentrations greater than 0.5 particles $cm^{-3}$ are reported.
n) If the "one CPC" method is adopted for the validation exchange the sampling line from the VPR outlet location (downstream) to the VPR inlet (upstream) and use a mass flow controller, or similar, to simulate the flow rate of the CPC from the VPR. If the "two CPC" method is adopted split the flow from the neutraliser between the upstream CPC and the inlet of the VPR.

*Note: if an aerosol generator that produces mono-disperse particles is used, the electrostatic classifier is not required and the VPR can be connected directly to the aerosol source via a neutraliser.*

o) Ensure that the particle residence time in the pipe work from the neutraliser to both the upstream CPC and the inlet to the VPR are identical. Residence time must be adjusted by varying the length rather than the diameter of the pathway, as diffusional deposition is independent of tube diameter for a given volumetric flow rate.
p) Set the electrostatic classifier flows such that the mono-disperse aerosol flow leaving the classifier is sufficient for the total inlet flow of both the CPC and the VPR (provide additional particle-free flow after the classifier if necessary, ensuring an adequate mixing length for the aerosol and particle-free air before the inlet of the CPC and VPR).

Make arrangements to log data from both the upstream (inlet) and downstream (outlet) CPCs simultaneously at the same sampling rate.

q) Generate the validation aerosol and connect the electrostatic classifier to the source.

r) For VPRs with variable dilution settings select nominal dilution settings on PND1 and PND2 typically used for DPF exhaust emissions measurements.

s) Select a mono-disperse diameter (30, 50 or 100 nm) using the electrostatic classifier and allow the number concentration to stabilise upstream of the VPR. All mono-disperse particles must enter the VPR at concentrations of greater than 5000 particles $cm^{-3}$. Once stable record measurements for 1 minute (or the time required for a cumulative number count of 10,000 particles, whichever is greater) up and downstream of the VPR.

t) The next mono-disperse diameter should then be selected on the electrostatic classifier and allowed to stabilise. Repeat step (s) for each mono-disperse diameter.

u) If the "one CPC" method is adopted each measurement must be stable and the upstream measurement must be verified after measuring the downstream concentration to ensure the inlet concentration has not drifted during the measurement, *e.g.* measure upstream concentration for 1 minute, measure the downstream concentration for 1 minute, then return to the upstream sampling arrangement and sample for 1 minute to ensure the concentration is stable (or the time required for a cumulative number count of 10,000 particles, whichever is greater). Measurement is valid if upstream particle concentration is within ±10 % of initial reading.

Once all required diameters have been measured the aerosol source should be disconnected from the VPR and a HEPA filter (class H13 of EN 1822:1998 or better filtration efficiency) applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 0.5 particle $cm^{-3}$). This ensures the VPR has not become contaminated from the calibration procedure.

A general schematic of the set up adopted by the consortium for the PCRF calibration is given in

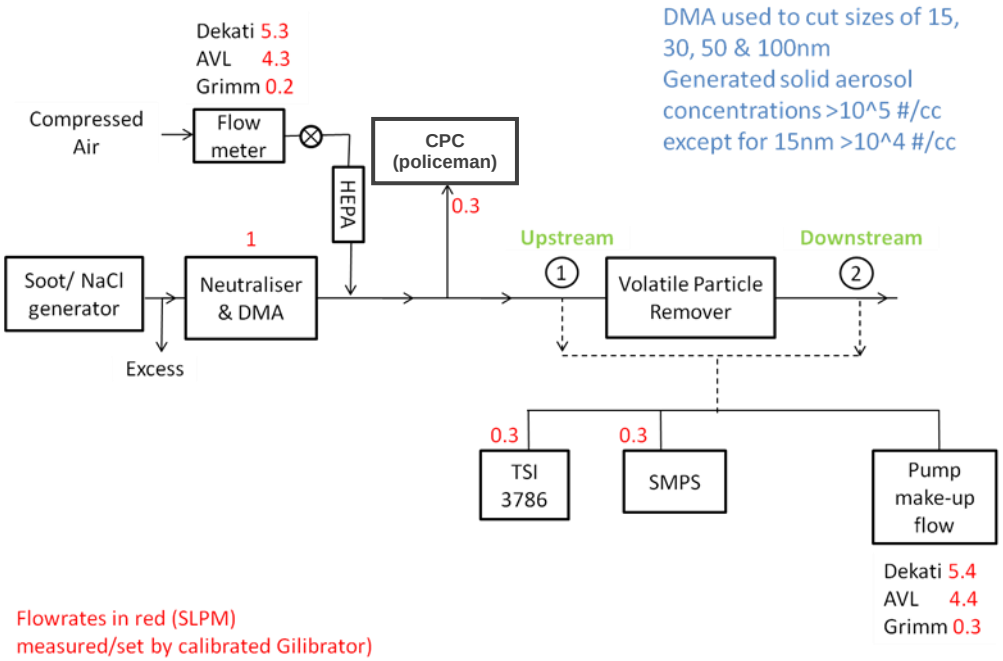


**Figure 11 Experimental set up adopted to conduct PMP PCRF experimentation**

It should be noted that PMP does not specify what type of solid aerosol should be used to perform the PCRF calibrations, and discussions within the SAE E31 highlighted that there may not be equal representativeness of different solid particle aerosols to actual Gas Turbine exhaust PM, thus, it was decided that within this study two solid aerosol generators should be investigated namely a salt nebulisers and a solid graphite soot generator (PALAS GFG 1000). Photographs of the aerosol generators used in this study are given below (Figure 12).

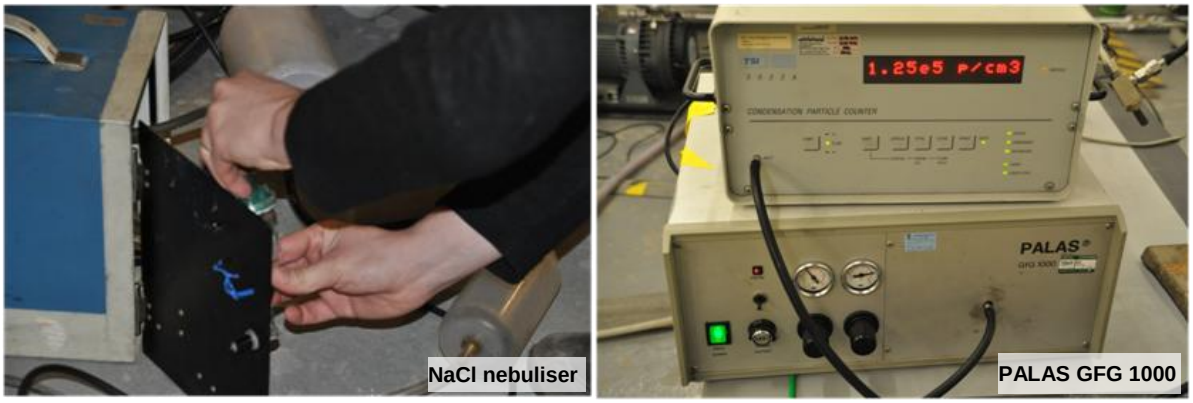


**Figure 12 Solid particle aerosol generators used for determination of PCRF calibration**

As discussed earlier the remit of this study was not to approve VPR technologies for use within the PMP methodology but to appraise their usefulness towards the measurement of non-volatile PM number for utilisation in the SAE ARP currently being developed. For this reason it was again deemed necessary to modify the PMP methodology to gain further insight into the potential of various VPR technologies for this purpose details of which are discussed below.

As at present the lower size cut-off for number measurement is still undecided for use within the SAE E31 non-volatile PM measurement ARP and may be lower than the 23nm adopted by PMP it was thought prudent to add another lower size classification for penetration studies compared with the PMP 30, 50 & 100nm cases. As such a 15nm case was also studied in this trial as it was thought that this could be representative of aerosol generated in modern large scale aero gas turbines. It was also thought by the consortium that the number concentrations permissible to conduct the PMP approach (>10000 particles $cm^{-3}$) were not high enough to be representative of modern gas turbine exhausts therefore higher particle concentrations of >100000 particles $cm^{-3}$ typically 200000 particles $cm^{-3}$ were utilised with the exception of the added 15nm case where it proved difficult to generate concentrations of sufficiently high concentration thus concentrations more analogous to the PMP protocol of >10000 particles $cm^{-3}$ typically 20000 particles $cm^{-3}$ were adopted.

Currently it is hard to predict the exact volatile PM loadings that are to be expected at the inlet of the VPR whilst measuring modern full-scale aero engines. It should be noted that volatile PM is an artefact of the sampling system, (as by definition there is no volatile PM at the exhaust plane of the gas turbine being measured) with different sampling configurations (dilution ratios, line temperatures, etc.) producing different volatile PM loadings for the same engine exhaust. As such until the SAE E31 Committee approved sampling system is designed, built and tested on numerous manufacturers' engines across a broad range of power

settings the volatile PM loadings that the VPR will witness at its inlet cannot be fully assessed.

### 4.3.2 PMP Validation of VPR for Volatile Particle Removal Efficiency

In order to meet the prescribed PMP specification for volatile particle removal efficiency the following must be achieved:

The VPR shall achieve >99.0 % vaporisation of 30 nm tetracontane ($CH_3(CH_2)38CH_3$) particles, with an inlet concentration of >10,000 $cm^{-3}$, by means of heating and reduction of partial pressures of the tetracontane when operated at the following conditions:

- Manufacturer's recommended evaporation tube temperature.
- VPRs with variable dilution factor settings: nominal secondary dilution factor of 10 (PND2), and the lowest PND1 nominal dilution setting.

The aforementioned PMP report prescribes a method for determining the volatile particle removal efficiency which may be conducted in two different ways depending on whether one or two CPC's are used for the study. Within this study only one CPC was used for calibration thus only this method is presented at this time.

The prescribed method which was broadly followed during this study is given below,

a) Position all apparatus according to the manufacturer's instructions; this should be something similar to that illustrated earlier (Figure 10).
b) Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (*e.g.* for rotating disc diluters remove the disc and clean using an appropriate solvent).
c) Perform any routine maintenance of the VPR as advised by the manufacturer (*e.g.* replacement of filters, tubing *etc.*).
d) Switch on the electrostatic classifier (or other source of monodisperse particles), CPC and VPR.
e) Fill the CPC with working fluid and allow the saturator and condenser to reach their specified temperatures.
f) Apply an external vacuum source to the CPC if not fitted with an internal pump.
*g)* Do not proceed unless all indicators on the CPC show correct instrument status (*e.g.* temperature, liquid level, flow and laser *etc.*).
h) Check the inlet flow rates of the CPC with an appropriate calibrated flow meter (low pressure drop variety recommended, *e.g.* bubble flow meter). The flow into the particle counter shall report a measured value within 5 percent of the particle counter nominal flow rate.
i) Check that zero concentration is reported when a HEPA filter (class H13 of EN 1822:1998 or better filtration efficiency) is attached to the inlet of the CPC. The CPC requires attention from the manufacturer if concentrations greater than 0.2 particles $cm^{-3}$ are reported.
j) If required, apply clean dry filtered air to the VPR at pressures specified by the manufacturer.
k) Connect the CPC to the VPR.
l) Do not heat the VPR, leave it at room temperature (upper limit of 35°C).

m) Connect a HEPA filter (class H13 of EN 1822:1998 or better filtration efficiency) to the inlet of the VPR and ensure a zero concentration is reported on the CPC. Do not proceed if particle concentrations of greater than 0.5 particles $cm^{-3}$ are reported.
n) Set the electrostatic classifier flows such that the monodisperse aerosol flow leaving the classifier is sufficient for the inlet flow of the VPR (provide additional particle-free flow after the classifier if necessary, ensuring an adequate mixing length for the aerosol and particle-free air before the inlet of the CPC and VPR).

*Make arrangements to log data from the CPC. Generate the validation aerosol and connect the electrostatic classifier to the source.*

o) Select 30 nm using the electrostatic classifier and allow to stabilise for at least 1 minute (or the time required for a cumulative number count of 10,000 particles, whichever is greater). The mono-disperse particles must enter the VPR at concentrations of greater than 10,000 particles $cm^{-3}$ (NB concentrations used in this study were typically 200000 particles $cm^{-3}$ for reasons discussed earlier). Once stable record measurements for 1 minute downstream of the VPR (or the time required for a cumulative number count of 10,000 particles, whichever is greater).
p) Switch on heating to VPR and allow to reach specified temperatures. Identical nominal dilution settings should be used at both temperature settings.
q) Continue to supply 30 nm tetracontane particles to the VPR and record the particle concentration from the CPC (at the downstream location).
r) When a stable downstream concentration is achieved, and the VPR has reached its temperature settings, record the downstream number concentrations over a 1 minute period (or the time required for a cumulative number count of 10,000 particles, whichever is greater).

*Once complete the aerosol source should be disconnected from the VPR and a HEPA filter (class H13 of EN 1822:1998 or better filtration efficiency) applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 0.5 particle $cm^{-3}$). This ensures the VPR has not become contaminated from the validation procedure.*

As discussed it was necessary to slightly modify the PMP recommendations in order that extra data could be collected, as such a slightly modified recommended PMP setup was utilised in this study and is represented schematically in Figure 13. As can be seen the setup is nominally identical to that prescribed by PMP with the exception that extra analysers along with a makeup pump were placed after the VPR to allow the differing flows required for each of the VPRs to be matched along with the ability to measure size distributions and organic aerosol mass.

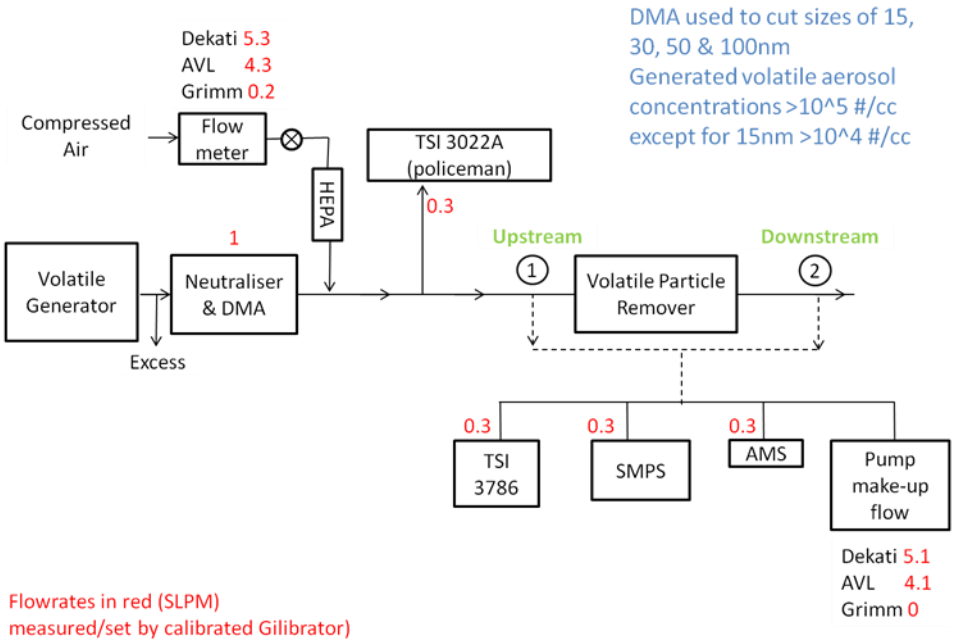


**Figure 13 Schematic of actual setup utilised for validation of VPR volatile particle removal efficiency**

It should be noted that the different flow rates were measured using a calibrated Gilibrator were utilised for each of the commercial VPRs (noted in red on the schematic (Figure 13)). This afforded a matched overall flow rate through the sample train experiment to experiment thus giving similar overall losses to the sample train.

Photographs of each of the commercially available VPR being tested for volatile particle removal efficiency are given in Figure 14. The results of this testing is presented later in section 4.4.

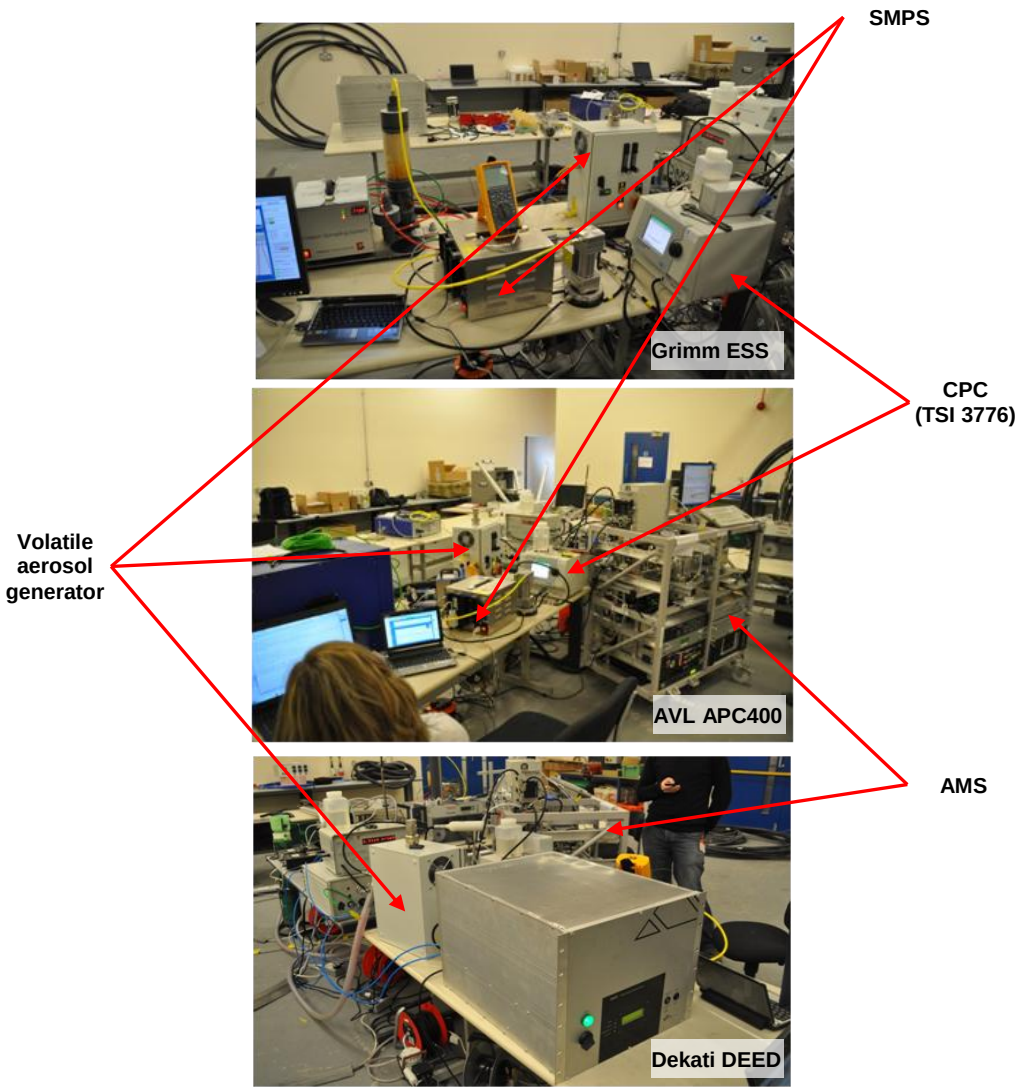


**Figure 14 Photographs of commercially available VPR being tested for volatile particle removal efficiency**

When the above method has been completed then the volatile removal efficiency is calculated as following:

The average number concentration of volatile particles at the inlet of the VPR should be calculated over the 1 minute stable period (or the time required for a cumulative number count of 10,000 particles, whichever is greater). The performance requirement of the VPR is that >99.0 % of tetracontane particles are removed. Therefore the pass criterion for the suppression of nucleation particles is 1 % of the inlet concentration.

The average number concentration at the outlet of the VPR should be calculated over the 1 minute (or the time required for a cumulative number count of 10,000 particles, whichever is greater) stable period, and if this is less than 1 % of the inlet concentration then the VPR performance is acceptable. A particle concentration reduction factor ($f_r$) must be applied to the downstream number concentration measurements. This factor is that calculated at 30 nm, for the same nominal dilution settings used in the primary calibration with solid particles.

There are two methods stated in the PMP protocol to calculate the Volatile Particle Removal Efficiency Criteria. However, only the method employed in this study will be discussed at this time and is defined as follows (5):

$$Average\ downstream\ concentration \times f_r(30nm) \leq \frac{Average\ upstream\ concentration}{100} \quad \textbf{(5)}$$

Where, $f_r$(30 nm) = particle concentration reduction factor at 30 nm and the same nominal dilution settings.

### *4.3.2.1 Design of Consortium Condensation Aerosol Generator*

The design of volatile particle generator is specified within the PMP report and a schematic of how the generator should be made is presented by Figure 15.

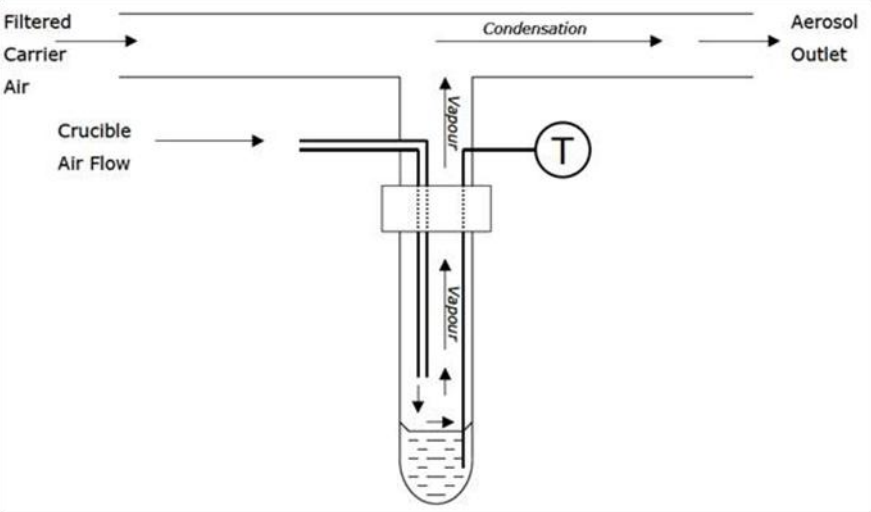


**Figure 15 Schematic of condensation aerosol volatile generator**

As can be seen the aerosol generator works on the principle of heating a volatile in a crucible to a sufficient temperature in order that some of the liquid phase volatile evaporates and saturates a filtered air stream that is passed through the crucible. The saturated warm filtered air is then forced to flow into a cold bypass air stream that cools the saturated volatile vapour causing a fraction of the vapour to condensate as an aerosol cloud of volatile particles. By changing the two filtered air flow rates and crucible preheat temperature it is possible to adjust the concentration and mean diameter of the aerosol cloud.

A bespoke condensation aerosol volatile generator based on the design provided in Figure 15 was designed and manufactured for this study photographs of which are presented in Figure 16.

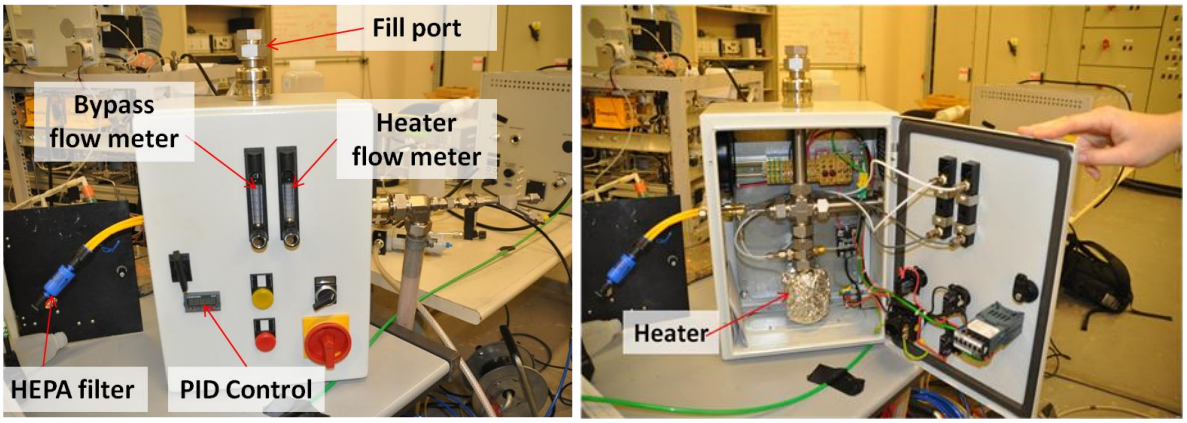


**Figure 16 Photographs of bespoke condensation volatile aerosol generator**

As discussed earlier PMP prescribes tetracontane ($CH_3(CH_2)38CH_3$) as the volatile substance to use in the determination of VPR volatile particulate removal efficiency, however as discussed earlier because the remit of this study was not to simply conduct a PMP validation of VPR technologies but to ascertain the applicability of particular VPR for use in a future SAE E31 Committee PM non-volatile number measurement ARP it was decided that other volatiles more representative of aero exhaust (*e.g.* Jet 'A' & Turbo lubrication oil) should be trialled, however these trials proved difficult to conduct due to the multi-component nature of these liquids which led to preferential distillation of the lighter products which made the variance in concentration over time too high to perform meaningful tests.

### 4.3.3 Calculation of Gas Reduction Factor (Dilution Ratio)

As discussed earlier a number of the VPR technologies particularly those designed for use in the PMP rely on multiple stage dilution. As such in order to calculate the actual non-volatile number concentrations that are being measured it is necessary to multiply the number concentration being measured by the CPC downstream of the VPR by the PCRF. As this PCRF is correcting for both diffusion losses of solid particles as well as the dilution factor brought about by the addition of clean dry filtered diluent it is necessary to determine that the dilution ratios assumed for the two dilution stages are correct by measuring the gas concentration reduction factor.

The PMP method for carrying out this procedure is given below:

A VPR quality control check should be performed under typical measurements conditions (*e.g.* those settings used to achieve particle concentration reduction factors, $f_r$ =150, $f_r$ =1500) and at the instrument manufacturer's recommended operation temperatures, in order to measure the corresponding gas concentration reduction factors. The upstream measurement of the undiluted gas concentration is not required if a certified gas is being used for the diluter quality control check. The only measurement that needs to be made is the diluted gas concentration downstream of the VPR.

Prepare the particle number system (VPR) for normal use.

a) Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer

b) Perform any routine maintenance of the VPR as advised by the manufacturer (*e.g.* replacement of filters, tubing *etc.*).
c) Prepare the appropriate calibrated gas analyser for use, following manufacturers guidance for stabilisation/warm up period.
d) Zero and span the analyser according to the manufacturer's instructions.
e) Connect the gas analyser to the VPR outlet (CPC position), ensuring that flow rates in the VPR meet the manufacturer's specifications.

*Supply the VPR with gas ensuring that the system does not become over pressurised. This can easily be achieved with a flow splitter at the inlet of the VPR to provide gas at ambient pressure to the first diluter while using a flow meter to confirm that excess gas is vented to an exhaust or by using a bag evacuated and then filled with the certified gas.*

f) Select the first dilution setting for checking and begin recording data from the analyser. Allow the downstream measurement to stabilise and record data for at least 2 minutes. Once a stable measurement has been recorded select the next dilution setting and allow to stabilise. Repeat this step for at least one other dilution setting.
g) If the VPR comprises more than one diluter, they must be measured as a complete system under the instrument manufacturer's recommended operation conditions.

Once the gas concentration reduction factor check is complete, then the analyser zero and span should be repeated to ensure analyser performance has not drifted during the procedure. The check is considered acceptable if the difference between the two zero and span measurements is less than 2 percent.

A schematic of the set-up required for the calculation of the gas reduction factor calibration is given below (Figure 17).

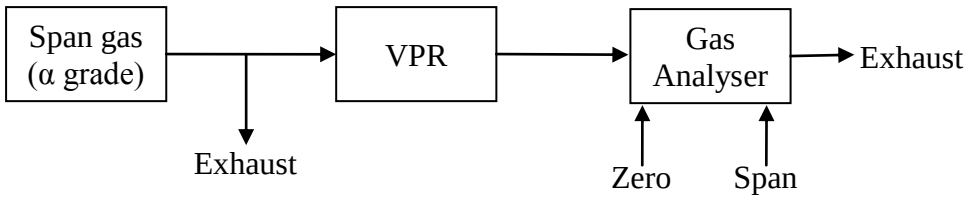


**Figure 17 Schematic representation of set-up for calculation of gas reduction factor**

The gas concentration reduction factor can then be calculated using equation (6).

$$Gas\ concentration\ reduction\ factor = \frac{Certified\ gas\ concentration\ (ppm)}{Average\ downstream\ gas\ concentration\ (ppm)} \quad \textbf{(6)}$$

## 4.4 Results of PMP Validation of Volatile Particle Removers

The results of individual experiments are presented over the following subsections with a summary of results in terms of PMP conformity presented later (Section 4.4.4)

### 4.4.1 Solid Particle Concentration Reduction Factor (PCRF)

As discussed earlier PMP does not specify the type of aerosol that should be utilised to carry out the investigation of solid particle penetration and the resulting particle concentration reduction factor. As discussed earlier in Section 4.3.1 both salt and graphite soot aerosols were investigated the results of which are discussed below.

#### *4.4.1.1 PCRF calculation using Salt nebuliser*

When studies were started utilising the salt nebuliser it was found that there were issues associated with the atomiser method available namely; it was an unstable source with high background readings**.** This coupled with discussions within the SAE E31 surrounding the representativeness of salt crystals as a comparison to gas turbine soot meant that only the AVL Particle Counter (APC), was appraised using salt (NaCl) aerosol.

The experimental set up as was discussed in Section 4.3.1 was utilised and a simplified schematic specific to the salt study is given in Figure 18. An atomiser was used to generate NaCl particles. Mono-disperse aerosol was achieved with a Long DMA (TSI 3081) and was split to the measurement instruments as shown; flow through a HEPA filter was added to equalise the flows.

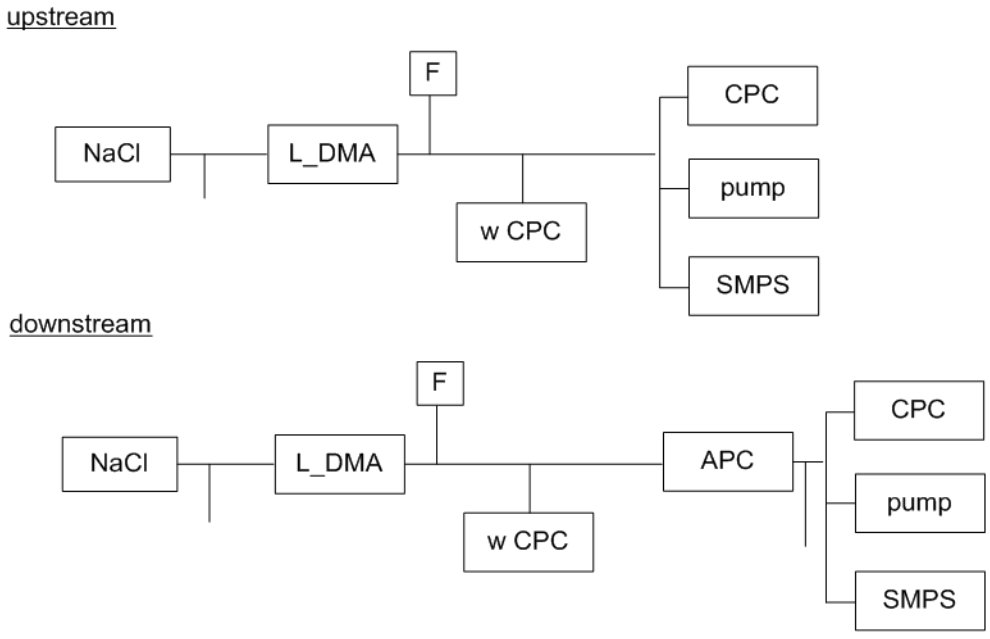


**Figure 18 Experimental set up: a) upstream measurements b) downstream measurements of the AVL APC400.**

A TSI 3085 water based CPC ($d_{50}$=5 nm) served as a monitor CPC, i.e. it was always connected after the DMA to check the stability of the calibration aerosol when the "upstream" and "downstream" measurements were conducted.

For the downstream measurements the AVL APC400 was connected in parallel with the 3085 water CPC. A SMPS from Grimm and a Grimm 5.414 butanol CPC ($d_{50}$=4 nm) or a TSI 3772 butanol CPC ($d_{50}$=10 nm) were used to measure the concentration downstream of the AVL APC400.

The AVL APC400 was set to PCRF 100 which as discussed earlier equates to a number concentration which has been corrected for both solid particle losses and gas reduction factor (dilution ratio) equal to 100 further details are discussed elsewhere (Giechaskiel et al. 2009) and (Giechaskiel et al. 2010a).

For the "upstream" measurements, the same SMPS from Grimm and Grimm 5.414 butanol CPC ($d_{50}$=4 nm) or TSI 3772 butanol CPC ($d_{50}$=10 nm) were used to measure the concentration at the exit of the DMA (upstream of the APC). A pump was used to increase the flow and to make it equal to the APC's flow (5 L/min). The reason is that if the flows are different during the upstream and downstream measurements, then different absolute levels are achieved due to the different dilution after the DMA.

Figure 19 shows the generated NaCl size distribution. The median is around 63 nm and the standard deviation is around 2. Table 4 shows the estimated percentages of doubly and triply charged particles that pass the DMA at the specific set sizes of 30, 50 and 100 nm. The multiply charged particles will result in overestimation of the PCRF results. An estimation of this effect can be given by equation (7):

$$Overestimation\ of\ the\ PCRF = a\,x + b\,y \qquad (7)$$

Where $a$ and $b$ are the doubly and triply charged percentages, $x$ and $y$ are the differences of the penetrations of the doubly and triply charged particles compared to the mono-disperse particles. For example, for the 50 nm PCRF, $a$ = 10.4%, $b$ = 0%. Assuming that the doubly charged particles have 20% better penetration than the 50 nm particles, then the overestimation of the PCRF is 10.4% x 20% = 2.1%. The effect is very small for all cases, so no correction for multiply charged particles was applied in the following results.

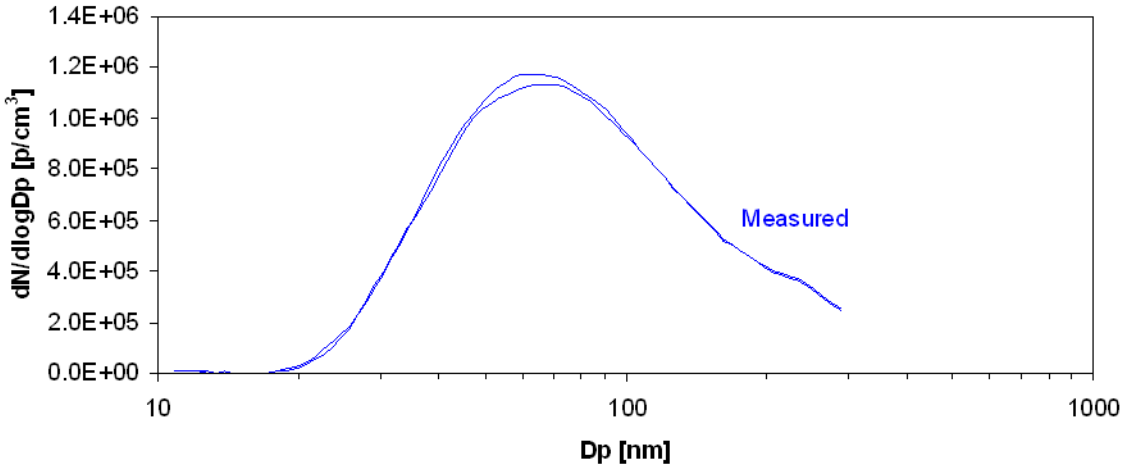


**Figure 19 Generated NaCl size distribution**

**Table 4** ***Estimated doubly and triply charged particles. The upstream of the DMA size distribution was assumed to have median 63 nm and standard deviation of 2. The equations can be found in the Supplemental Information of Giechaskiel et al. 2010b.***

| PCRF check | Doubly charged (*a*) | Triply charged (*b*) |
|---|---|---|
| 30 nm | 4.4% | 0% |
| 50 nm | 10.4% | 0% |
| 100 nm | 17.8% | 4.7% |

The results of the SMPS can be seen in Figure 20 and shows the size distribution of the mono-disperse aerosol upstream and downstream of the AVL APC400. The existence of multiply charged particles can be hardly noticed at the 50 and 100 nm cases due to the high background of the set up. There is no clear explanation for the high background (i.e. when the DMA voltage off). The width of the size distribution can be explained by the low sheath to sample ratio.

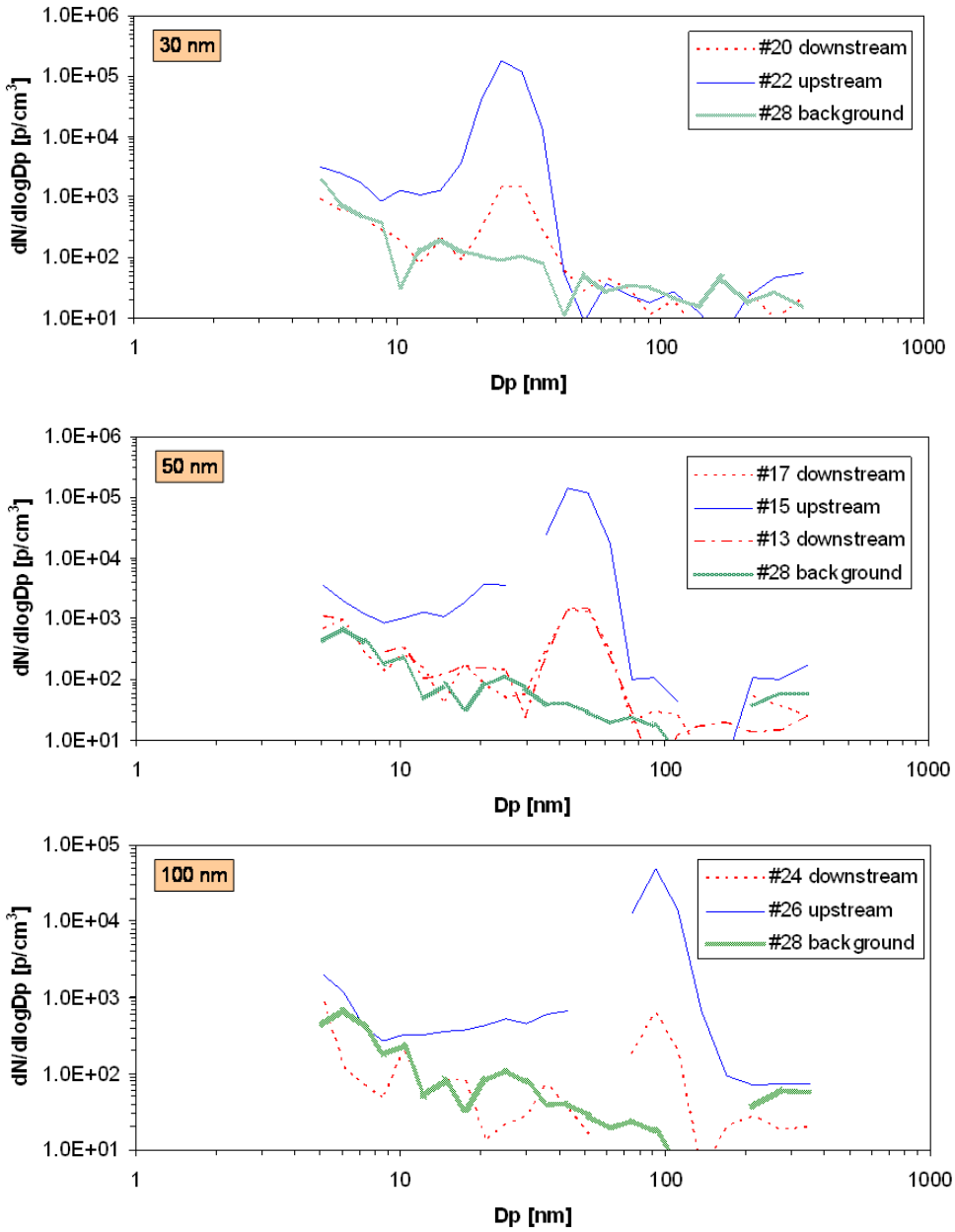


**Figure 20 Size distributions of the mono-disperse aerosol upstream and downstream of the AVL APC400 (please note the caption numbers are associated with experiment number).**

**Table 5 Measured 30, 50 and 100 nm PCRFs with different instruments**

| | 30 nm | 50 nm | 100 nm | average |
|---|---|---|---|---|
| SMPS up / down (background corr.) | 80 | 76 | 94 | 83 |
| 5.414 up / down | 97 | 75 | 80 | 84 |
| 3085 / 3790corr | 143 | 92 | 89 | 108 |
| 3085 / 3772 | 135 | 98 | 41 | 91 |
| 3772 up / down (background corr.) | 107 | 80 | 100 | 96 |

Table 5 shows the PCRFs of the AVL APC400 for 30, 50 and 100 nm as calculated by dividing the upstream and the downstream total concentrations calculated from the SMPS size distributions. The average PCRF is around 50 which is half of the expected value of 100 (which was set at the APC). However, taking into account the high background, the calculated average PCRF is 83.

Figure 21 shows the real time recordings of the TSI 3085 water CPC (upstream of the APC), the TSI 3790 CPC downstream of the VPR and the SMPS scans that were discussed above. The recordings of the Grimm 5.415 CPC, which were used for both upstream and downstream measurements, were lost. However, based on some notes during the measurements the average PCRF is 84 (Table 5). Dividing the 3085 and the 3790 the estimated PCRF is 169 (Table 5). However, the 3790 has a cut-off size at 23 nm, thus it cannot measure all particles during the 30 and 50 nm measurements (Figure 20). Taking into account the counting efficiency of the CPC for NaCl (Wang et al. 2010) and the size distributions downstream of the APC (Figure 20) a percentage of counted particles is calculated. Using this percentage to correct the 3790 results the corrected PCRFs of Table 5 are estimated. The average PCRF is 108.

One important point from Figure 21 is that the total number concentration measured by the water CPC and the SMPS do not always match. For example for the 50 nm tests (test #15), the water CPC measures higher, at 30 nm the two instruments measure the same (test #22) and at 100 nm the water CPC measure much higher (test #26).

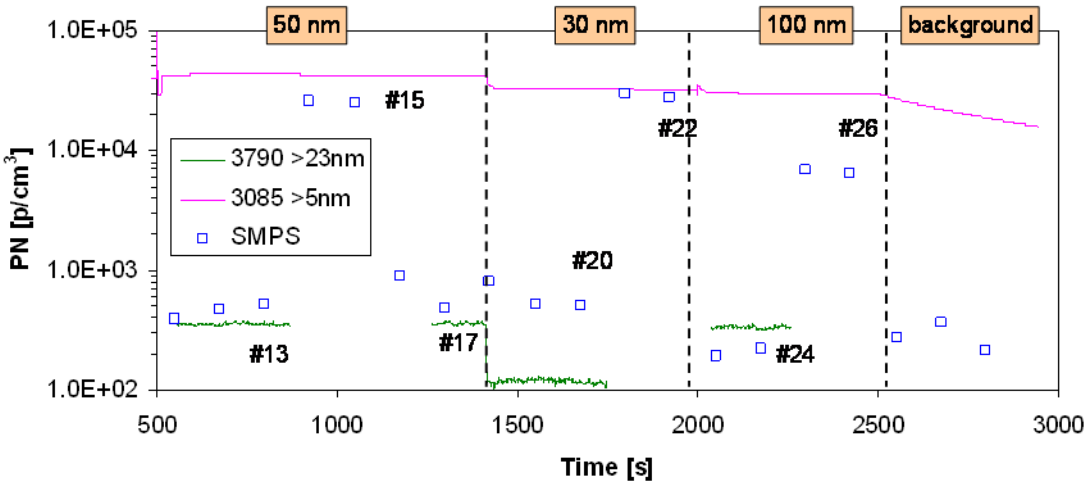


**Figure 21 Recorded particle concentrations, with the TSI 3085 (water CPC) upstream, the TSI 3790 downstream and the SMPS measuring upstream and downstream of the AVL APC400.**

Similar tests were repeated owing to the aforementioned loss of the Grimm 5.414 CPC data. This time another CPC was used (TSI 3772 with $d_{50}$=10 nm). No SMPS was used due to time restrictions. The results can be seen in Figure 22. The 3085 (water CPC) gave different concentrations compared to the TSI 3772 when both were measuring upstream of the AVL APC400. For the 100 nm case the TSI 3085 was measuring lower, for the 50 and 30 it was measuring higher. Again there is no explanation for the difference in number concentrations witnessed between the CPCs. Partly this can be explained by the high concentrations which were above the counting range of the 3772 (its max is 10000 particles/cm$^{-3}$). Another explanation is the different cut-off size of the instruments, although no particles are expected at the range of 5-10 nm after the DMA. The TSI 3772 gave similar results with the TSI 3790

when both were measuring downstream of the APC for the 100 nm case. However the TSI 3790 was measuring lower at 50 and 30 nm cases, due to the higher cut-off size it has ($d_{50}$=23 nm).

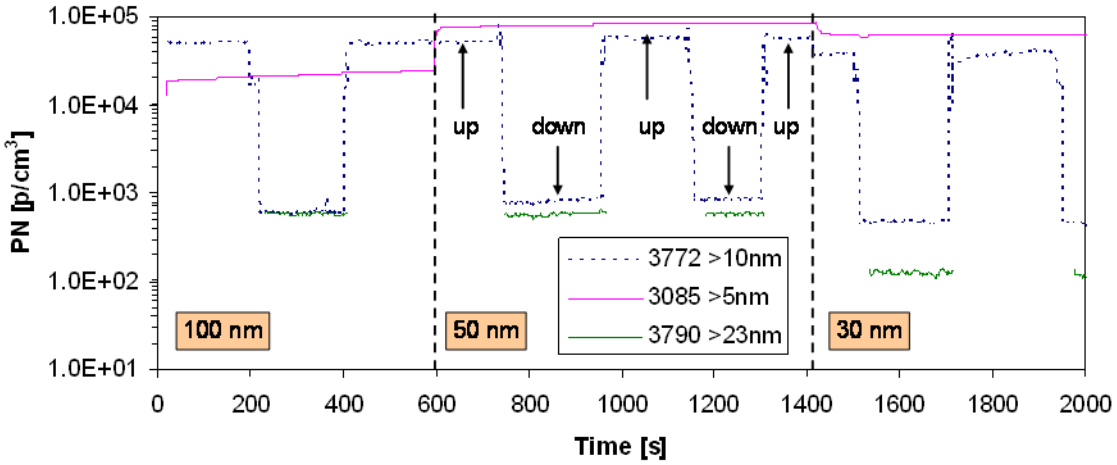


**Figure 22 Recorded particle concentrations, with TSI 3085 (water CPC) upstream, the TSI 3790 downstream and the TSI 3772 measuring upstream and downstream of the AVL APC400.**

**Table 6 Measured 30, 50 and 100 nm PCRFs with different instruments.**

| | 30 nm | 50 nm | 100 nm | average |
|---|---|---|---|---|
| SMPS up / down (background corr.) | 80 | 76 | 94 | 83 |
| 5.414 up / down | 97 | 75 | 80 | 84 |
| 3085 / 3790corr | 143 | 92 | 89 | 108 |
| 3085 / 3772 | 135 | 98 | 41 | 91 |
| 3772 up / down (background corr.) | 107 | 80 | 100 | 96 |

The average PCRF using the ratio of the 3085 and 3772 was calculated 91 (Table 6). The average PCRF using the results of the 3772 upstream and downstream of the AVL APC400 was 80. Taking into account the background it was 96.

Thus after calibrating the AVL APC400 using mono-disperse NaCl particles using numerous CPCs (checked for linear response to minimise effects on the results) and an SMPS. The measurements of the PCRFs of an AVL APC400 at 30, 50 and 100 nm gave average PCRF's within -17% and +8% of the set value dependant on CPC used, however the value gained utilising the PMP approved CPC was -4% (within the PMP recommendations of -5% to +30%). This indicates that the AVL APC400 is working properly. However, it should be noted that the uncertainty of the results are very high, with the following reasons being suggested:

- The upstream and downstream measurements were not identical due to small changes in the flows during the upstream and downstream measurements. Typically the calibration aerosol concentration changes <1-2%. In these tests it changed around 10% (which still adheres to PMP protocol).
- There was high background concentration of the specific set up.

- Some instruments were found to be noisy (e.g. the water CPC)
- Some instruments were not suitable for the added 15nm non-PMP measurements (e.g. the 3790 for the 15 nm test due to the high cut-off size at 23 nm)

#### *4.4.1.2 Solid Particle Penetration efficiency using PALAS GFG1000*

As discussed earlier (Section 4.3.1) a PALAS GFG1000 spark discharge solid graphite soot particle generator was used to generate a solid aerosol to be used in calculating the PCRF as discussed in Section 4.3.1. This solid PM generator was used in a test set-up depicted earlier in (Figure 11) and typical size distributions for the various particle diameters (15, 30, 50 & 100nm) as selected by the DMA and measured by the downstream SMPS are given in Figure 23. It is witnessed that the cut size distributions are wider than would be expected this is attributed to the low ratio of sheath to aerosol sample flow within the DMA column. This low ratio was necessary to provide the high sample flow required by the measurement instruments required in this study. The ratio was typically 3-4:1 compared to the ratio of 10:1 normally adopted.

As can be seen with a constant soot source varying the desired particle mean diameter using a DMA gives varying overall number concentrations for each of the four sizes examined. It can be observed that the fewest particle loadings are witnessed at 15nm and the highest concentrations at 50nm.

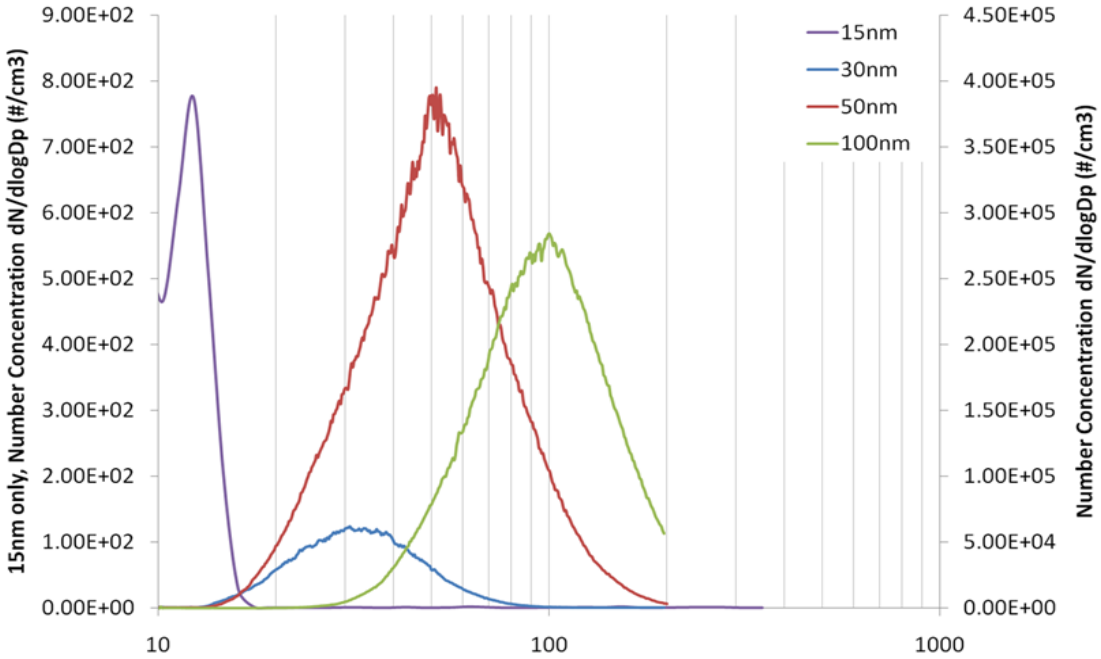


**Figure 23 Size distribution of DMA cut 15, 30, 50 & 100nm particles as measured during PCRF calibration**

Each of the VPR technologies (PMP and non-PMP approved) as discussed in Section 4.2 were tested for penetration efficiency as outlined by the methods described in Section 4.3.1, for mean particle sizes of 30, 50 & 100nm as prescribed by PMP along with an extra added 15nm data point thought to be useful for comparison with a typical full scale modern aero gas turbine engine exhaust.

The penetration efficiencies recorded are presented graphically for each of the VPR technologies in Figure 24. As would be expected from theoretical modelling the highest losses in each of the VPR are observed at the lower size distributions, with relative losses reducing as this size is increased. It is also observed that the VPR with the best penetration for all particle sizes is the Dekati DEED, followed by the AVL APC400, consortium bespoke, Grimm ESS and finally the Catalytic stripper.

It can be seen when looking at 15nm particles 20% of all particles are lost in the VPR with the highest penetration efficiency the Dekati DEED compared to a loss of 65% witnessed by the bespoke CS with the other units displaying losses of 32-45%. As explained earlier there are lower losses witnessed at the higher particle diameters with the PMP approved Dekati DEED VPR displaying average losses over the 30, 50 and 100nm range of approximately 10% and the AVL APC400 witnessing approximately 20% loss, followed by the consortium bespoke at approximately 27%, Grimm ESS at approximately 33% and finally the bespoke CS at 45%. It should be noted that unfortunately when processing the CS data there was an error in the data taken for the 30nm case hence the data points omission from Figure 24.

As discussed earlier the PMP does not currently stipulate a minimum penetration that must be attained as this loss is corrected for in the PCRF. However, the losses of the different sizes must be within a certain percentage of the losses witnessed for the 100nm case as outlined in equations (3) & (4) in Section 4.3.1.

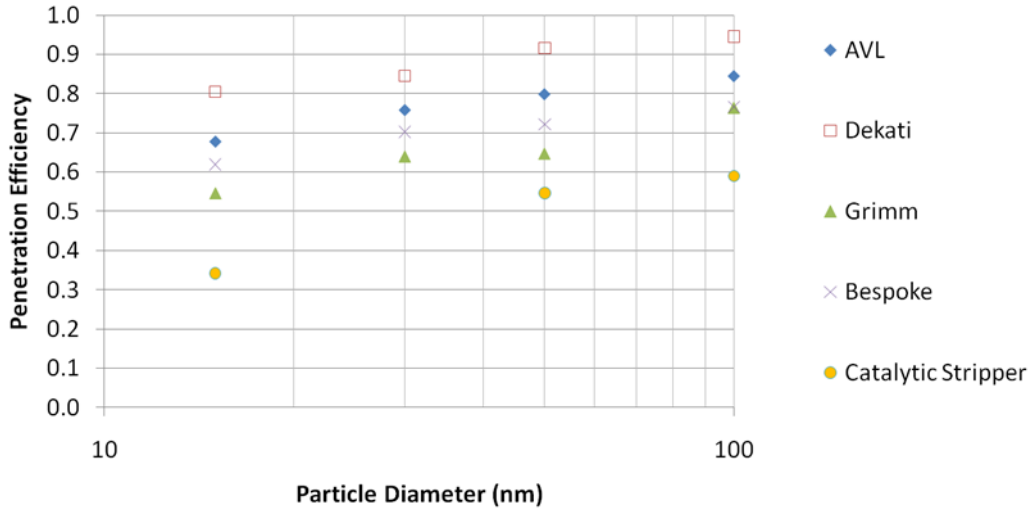


**Figure 24 Penetration efficiency of solid graphite particles for various VPR investigated**

Details of the relative PMP pass requirements for PCRF are summarised and discussed later within the PMP pass requirements (Section 4.4.4) so are not discussed further at this time.

As an aside an inter comparison of two CPC's was conducted to investigate the representativeness of a TSI water 3783 based CPC against the more conventional TSI 3776 butanol based CPC on the PALAS solid graphite spark soot generator. The results of the comparison are given below in

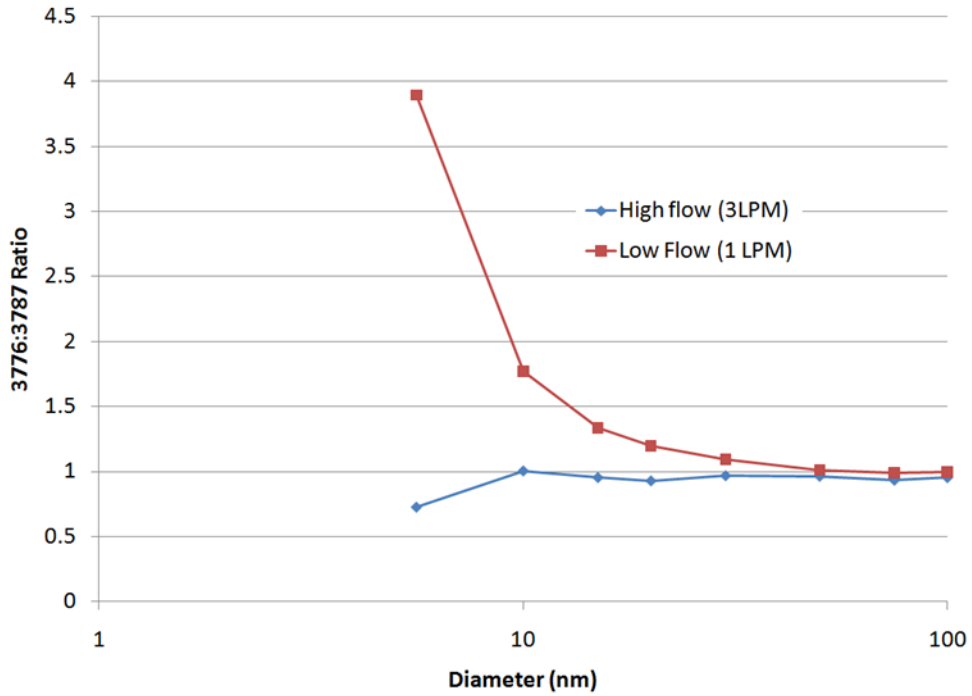


**Figure 25 CPC inter comparison between water based TSI 3787 versus TSI 3776 butanol based**

As can be seen on high flow condition there was excellent agreement between the two analysers which means water based CPC's which can be used with lower levels of risk associated with the transport and use of butanol (which is both flammable and toxic), along with a higher potential single count mode should be considered in the future.

### 4.4.2 Volatile Particle Removal Efficiency

#### *4.4.2.1 PMP Approach Volatile Particle Removal Efficiency*

The volatile particle removal efficiency for each of the VPR discussed earlier in Section 4.2 was tested utilising the methods highlighted in Section 4.3.2. The results of this study are summarised graphically in Figure 26 which plots the removal efficiency against mean particle diameter for each of the VPR tested.

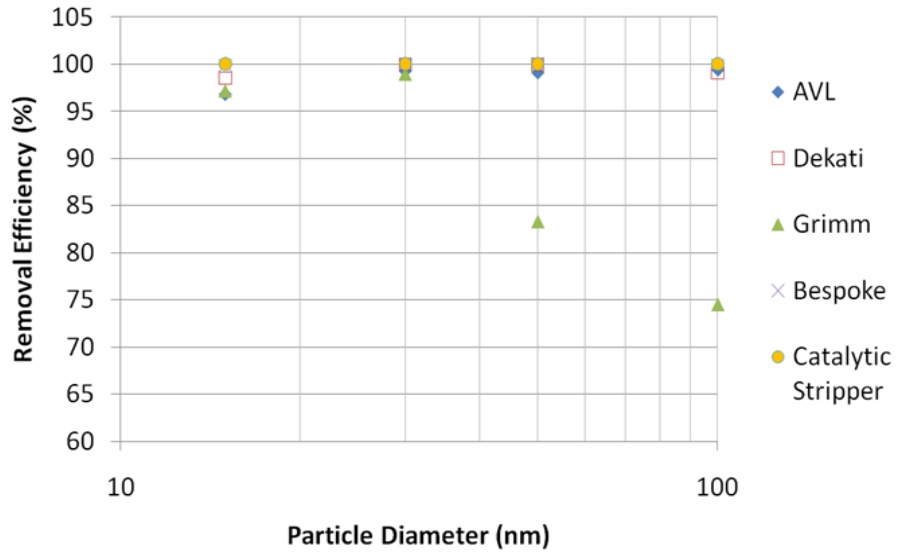


**Figure 26 Volatile particle removal efficiency across a various size ranges for each of the tested VPR**

It may be observed that with the exception of the Grimm ESS which was unable to achieve the PMP required volatile particle removal efficiency, that the other four VPR types appear to perform well in terms of volatile particle removal efficiency over all of the size ranges studied and achieve the >99% removal over the three PMP specified size ranges of 30, 50 & 100nm particle mean diameter. This fact is highlighted in Figure 27 which is another plot of the data given in Figure 26 with the removal efficiency axis scale adjusted to allow a closer inspection of removal efficiency across the size range. It should also be noted that the removal efficiencies observed here were measured with a non-approved PMP CPC with a lower cut off of 7nm compared to the 23nm units typically used. Thus it can be surmised that if a PMP type CPC had been utilised then the removal efficiencies witnessed would have been higher.

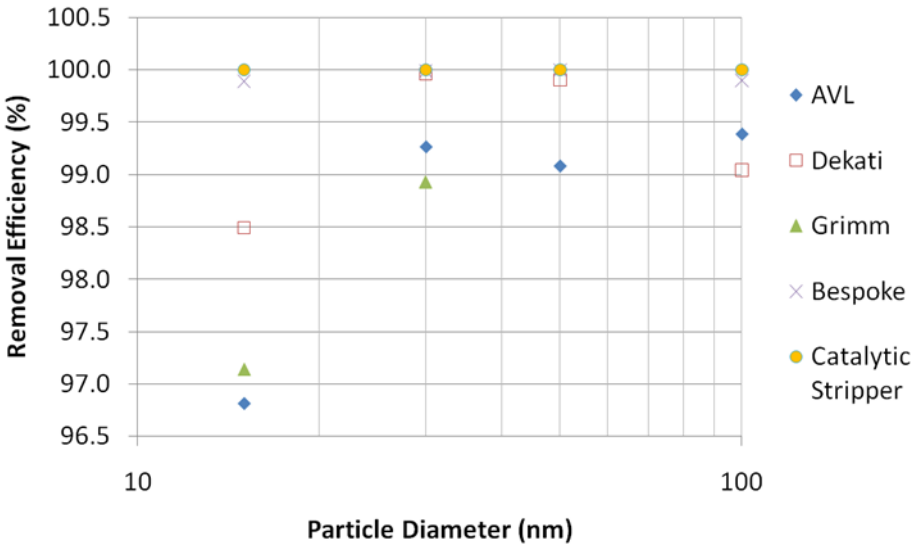


**Figure 27 Focused scale highlighting volatile particle removal efficiency for different particle diameters for each of the tested VPR**

On further inspection of the data presented in Figure 27 it is witnessed that the PMP approved VPR namely the Dekati DEED and the AVL APC400 even though achieving the PMP

requirements do not perform as well as the two bespoke VPR systems namely the SAMPLE III consortium built VPR and University of Minnesota built CS. It is observed that both the bespoke systems achieve >99.8% removal efficiencies across all of the tested size ranges with the bespoke CS witnessing approximately 100% removal of all of the tetracontane particles.

For the non-PMP approved test point at 15nm included for this study it can be seen that both the Dekati DEED and AVL APC400 appear to show lower removal efficiencies of 98.5% and 96.7% respectively. Although removal efficiencies appear to be still very high it should be highlighted that even if only 1-3% of volatile particles are penetrating the VPR then this could add a fairly large error to the solid particle non-volatile number count which could in certain circumstances have much lower number concentrations compared to the volatile fraction. However, the authors concede that these low size measurements have higher levels of uncertainty with them hence these reductions in efficiency may be attributed to measurement error.

It is proposed that the increased removal efficiency witnessed by the two bespoke systems may be attributed to a number of factors. In the case of the consortium bespoke VPR which is very similar to the Dekati DEED in terms of design the increased removal efficiency witnessed may be attributed to a number of factors specifically changed in its design to allow for higher removal efficiencies namely higher primary dilution temperature (300°C versus 150°C), higher evaporation tube temperature (400°C versus 300°C) and a longer evaporation tube residence time (1sec versus ~0.2sec). As for the University of Minnesota CS the technology is different so it may be assumed that the increase in removal efficiency was brought about due to the actual oxidation of the volatile material which prevents re-nucleation. However, it should also be noted that the CS had much lower penetration efficiencies compared to the other VPR as was discussed earlier in Figure 24 which would also account for the increases in removal observed particularly for the smallest 15nm particles of which 65% could have been lost due to diffusion losses however, other studies conducted at the University of Minnesota have indicated that 50% losses would be expected at 15nm highlighting the increased uncertainty associated with measuring at these small sizes <20nm.

As was shown and discussed earlier (Figure 26) the Grimm ESS displayed the worst removal efficiencies across the range of particle sizes. The authors suggest that the reason this is witnessed is due to the systems design which is only capable of heating the volatile to 200°C compared to the >300°C of all of the other VPR. The Grimm ESS in its design also actively cools the sample at the stage the other VPR are using high temperature evaporation tubes prior to secondary dilution which the authors feel may allow re-condensation of the partially evaporated volatile PM hence the penetration of volatile PM particularly at larger sizes to the exit of the VPR.

#### *4.4.2.2 Non-PMP Approach Volatile Particle Removal Efficiency using the AVL APC400*

It was decided after interpretation of the PMP approved volatile particle removal efficiency results that further fundamental work on pure volatile PM removal was still required. Unfortunately as the majority of the VPR had been returned to their respective manufacturers this study could only be conducted using the AVL APC400. In this experiment the raw

exhaust of the consortium built condensation aerosol generator (described earlier in Section 4.3.2.1) was measured upstream and downstream of the AVL APC400 using an SMPS.

By changing the evaporator temperature and relative bypass flow rate of the volatile generator it was possible to produce both a low volatile PM number concentration case which is presented in Figure 28 and a high volatile PM number concentration case which is given by Figure 29.

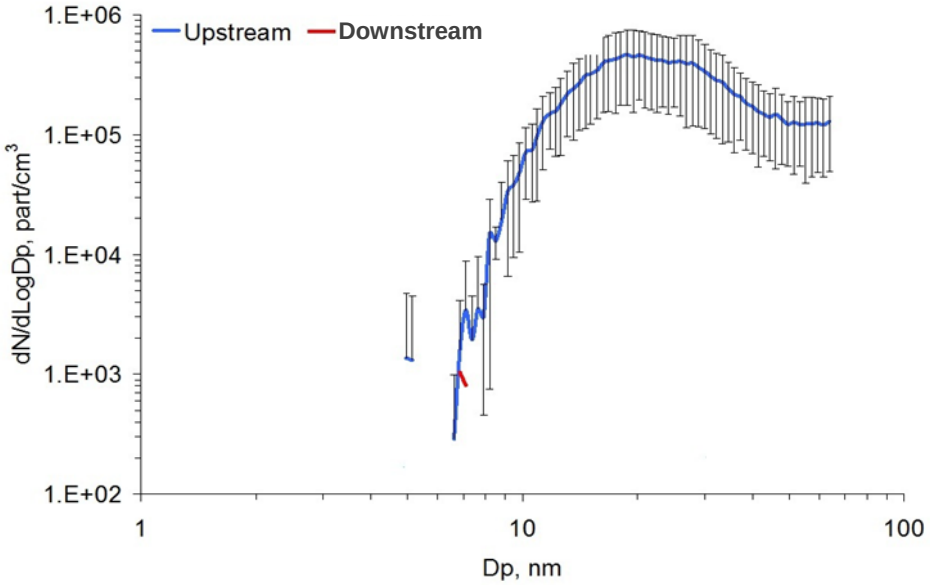


**Figure 28 SMPS plot of low number concentration volatile PM produced by consortium condensation volatile aerosol generator upstream and downstream of AVL APC400 VPR**

It can be seen in the low volatile PM number case presented in Figure 28 that the PM volatile entering the AVL VPR (depicted as blue distribution) seems to be nearly totally removed from the exhaust of the AVL APC400 as depicted by the lack of a noticeable downstream distribution (red line). However, when the high volatile PM number concentration was investigated as represented graphically in Figure 29 it is observed that there do see appear to be a measureable number of volatile PM across a broad size range penetrating the AVL VPR.

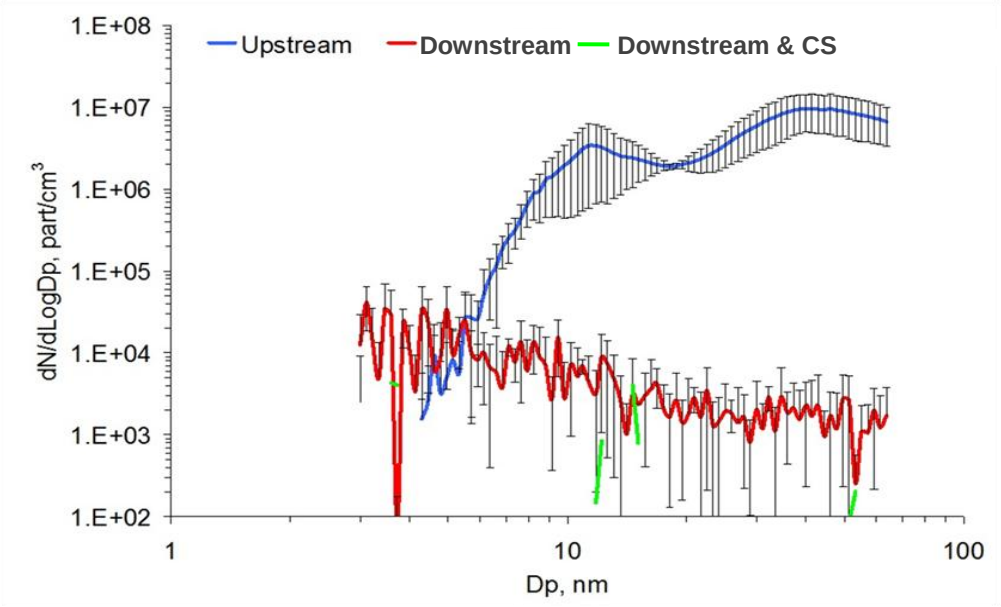


**Figure 29 SMPS plot of high number concentration volatile PM produced by consortium condensation volatile aerosol generator upstream, downstream and downstream with additional CS of AVL APC400 VPR**

Interestingly it is noted that higher numbers of smaller <7nm particles are seen in the exhaust of the VPR than are measured upstream of the inlet, this highlights the fact that volatile particles are shrunk in the VPR but not totally removed. This graph coupled with the knowledge gained from the removal efficiency for the AVL VPR calculated via PMP method (Figure 27) which shows that >99% of particles are being removed demonstrates that for a high concentration poly-disperse volatile aerosol it is possible to witness large number counts of volatile PM particularly at a size range cut off smaller than those specified by PMP protocol (23nm). Thus, it is important to note that there could be sizable errors introduced into non-volatile PM number measurements brought about by the counting of volatile PM that penetrates the VPR with its effect being greater the smaller the lower size cut off that is adopted.

In order to try to completely remove the volatile PM before measurement it was then decided to replace the traditional evaporation tube in the AVL APC400 with the 1.5LPM University of Minnesota CS prototype, as can be seen in Figure 29 the volatile fraction after the VPR & CS in series seems to have nearly been removed (as depicted by the lack of a continuous green line). Thus use of a CS could reduce the uncertainty of non-volatile PM number measurement if PMP type VPR are proposed for the SAE E31 Committee ARP, however it should be noted that as demonstrated by the consortium bespoke VPR that slight modifications to the PMP VPR in terms of increased temperatures and residence time may also be capable of reducing this uncertainty.

### *4.4.2.4 Non-PMP Approach Volatile Particle Removal Efficiency appraisal using volatile coated particles*

It was decided to conduct a volatile coating removal experiment by passing particles generated by the PALAS solid graphite spark soot generator, through the consortium bespoke condensation volatile aerosol generator containing aviation turbine lubrication oil. These coated particles were then either passed through the consortium bespoke VPR of through the University of Minnesota CS. The data from this experiment is presented in Figure 30.

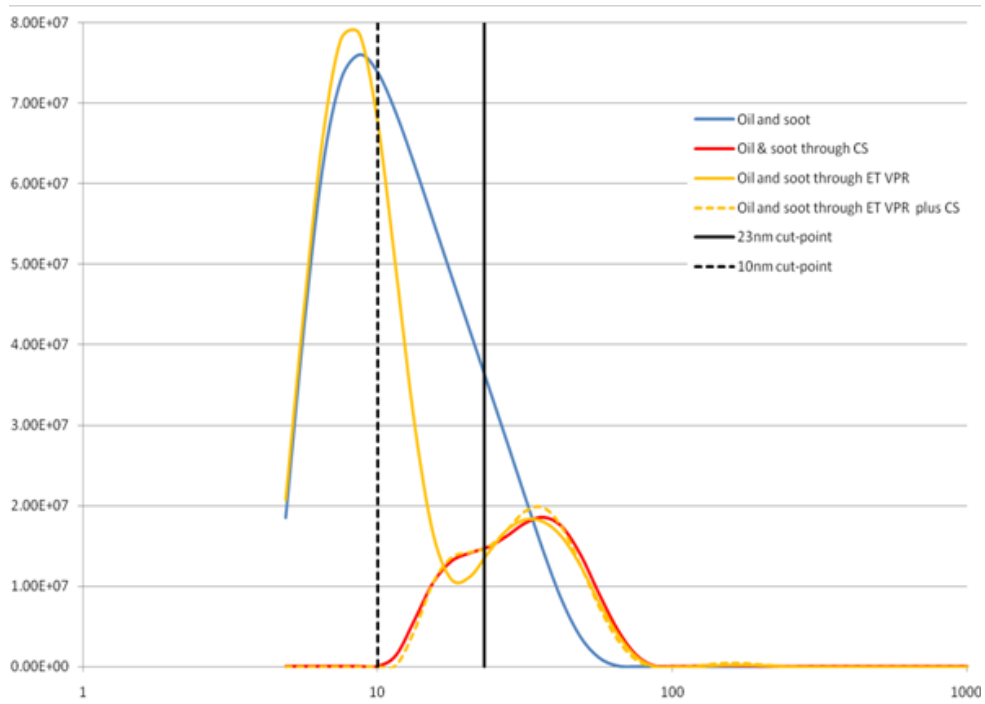


**Figure 30 DMS data showing volatile coating removal from solid graphite particles.**

The raw sample upstream of the VPR is shown as a mono-modal peak (blue line) of volatile coated particles. The sample was then passed through a CS and it is noted that there is a reduction of particle number to a new size distribution (red line) which is assumed to be the solid particle size distribution. The output from the consortium bespoke VPR (solid yellow line) displays a large nucleation mode peak at a mean diameter of approximately 8nm. Thus it can be seen that the lower size cut off selected would determine whether the VPR had been effective in removing volatile PM as if a 23nm lower cut off is selected the VPR would show a size distribution with excellent agreement with the CS. However, if a lower cut off of 10nm was selected then the bespoke VPR would give number counts orders of magnitude higher than the actual solid particle number concentration with the lower the cut off selected the worse the accuracy.

#### *4.4.2.4 Non-PMP Approach Volatile Particle Removal Efficiency appraisal using an Aerosol Mass Spectrometer (AMS)*

Added to the PMP approved volatile particle removal efficiency experiment was the measurement of volatile penetration through the VPR using an aerosol mass spectrometer (AMS) as highlighted in Figure 13. The AMS has been described in detail in previous studies (SAMPLE & SAMPLE II) therefore will not be discussed at this time.

The AMS measures volatile components in term of mass, however it cannot give a true zero appraisal as it has a lower measurement sensitivity of ~ 0.5 µg/m$^3$. It also has a lower size sensitivity of ~35nm thus the added 15nm particle diameter data point was not appraised with this method. The results of the AMS experiment for the three commercially available VPR is presented below in Table 7.

**Table 7 Volatile particle removal efficiency of numerous VPR measured using AMS**

| VPR | Organic aerosol mass (µg/m$^3$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 30nm | | 50nm | | 100nm | | Full size distribution | |
| | Up | Down | Up | Down | Up | Down | Up | Down |
| **AVL** | 0.5 | 0 | 3 | 0 | 5 | 0 | 288 | 0 |
| **Dekati** | 0.5 | 0 | 1 | 0 | 12 | 0 | 350 | 0 |
| **Grimm** | 0.5 | 0 | 4 | 0 | 6 | 0 | 323 | 0 |

As can be seen the commercially available VPR were tested for the three PMP recommended mono-modal PM sizes of 30, 50 & 100nm as well as being tested with a poly-dispersed aerosol and it is witnessed that for all cases in terms of mass each of the VPR technologies reduced all of the volatile PM in terms of mass below the sensitivity of the AMS. Thus for the high loading cases (full size distribution) it can be calculated even taking into consideration the minimum measurement sensitivity that in terms of mass there is a volatile removal efficiency of >99.8%.

However, as discussed earlier the lower size sensitivity of the AMS is ~35nm therefore it is not surprising that there was minimal mass measured in the range >35nm as the PCRF experiments described in Figure 28 suggest that the majority of particles are shrunk to less than this limit at least in the case of the AVL APC400.

### 4.4.3 Gas Reduction Factor (Dilution Ratio)

The gas reduction factor as described in Section 4.3.3 was calculated for both the PMP approved VPR studied during this remit of work namely the Dekati DEED and the AVL APC400. The data derived for the Dekati DEED running at a PCRF value of 100 as measured using a Signal Instruments 3000HM heated FID is presented below in Table 8.

**Table 8 Calculation of Gas Reduction Factor for Dekati DEED**

| Span Gas | Analyser Range | Reading | Dilution Ratio |
|---|---|---|---|
| **Zero** | 10% | 0.0% | |
| **9%** | 10% | 0.11% | 81.82 |
| **9%** | 4000ppm | 1117ppm | 80.57 |
| **Zero** | 4% | 0.0% | |
| **2.70%** | 4% | 330.0ppm | 81.82 |
| **2.70%** | 400ppm | 343.2ppm | 78.90 |
| **903ppm** | 1000ppm | 15.0ppm | |
| **903ppm** | 40ppm | 15.6ppm | |
| **Zero** | 40ppm | 4.0ppm | |
| **903ppm** | 1000ppm (zero corr.) | 11.0ppm | 82.09 |
| **903ppm** | 40ppm (zero corr.) | 11.6ppm | 77.84 |
| | | ***Average*** | ***80.78*** |

As can be seen numerous test points were undertaken using varying alpha grade span gases (9%, 2.7% & 903ppm) as the inlet gas and data then generated for the different analyser ranges to ensure analyser linearity effects were minimised. It can be seen that any drift in the analysers zero is used to correct the reading then gas reduction factors (dilution ratio) calculated as specified in equation (6).

The AVL APC400 was tested utilising a similar approach using a Signal Instruments MGA9000 NDIR $CO_2$ analyser and it was found that the gas reduction factor witnessed when the instrument was set to a PCRF of 100 was 73.

Due to the different natures of the non-PMP approved VPR it was not always possible to calculate the dilution ratio by the gas reduction factor by the measurement of gases. In the case of the consortium bespoke VPR due to the variable temperatures of inlet, diluent and evaporation tube the dilution ratio would change with varying diluent supply pressure hence gas dilution factors were calculated each time the unit was tested behind a smoke source by measurement of $CO_2$ upstream and downstream of the VPR using two separate NDIR $CO_2$ analysers with suitable ranges of 5000ppm & 1000ppm respectively.

Due to the re-circulating nature of the Grimm ESS which filters a portion of the exhaust gas, which is then used as the diluent, it is not possible to calculate the gas reduction factor by measuring gas concentrations.

Unlike the other technologies the CS does not use a diluent stage to remove the volatiles thus there is no reduction of gaseous species within the unit so this was also not examined.

### 4.4.4 Summary of PMP Conformity for VPR technologies

Apart from design specifications in terms of design, dilution ratios and temperatures of evaporation tube and diluent to be used as described earlier in Section 4.2. There are two major performance criteria that must be met in order to adhere to PMP protocol and these are with respect to PCRF and volatile removal efficiency as discussed earlier in Section 4.3.

The results for each of the tested VPR in relation to the pass criteria of PMP for PCRF and volatile removal efficiency are given in Table 9. The table is colour coded to show if the particular criteria are met with green illustrating compliance, orange illustrating non-compliance and light blue illustrating test not detailed by PMP.

**Table 9 PMP PCRF and volatile removal efficiency pass Criteria summary for various VPR**

| VPR | PCRF ratio pass between x > y | | | Volatile removal efficiency pass >99% | | | |
|---|---|---|---|---|---|---|---|
| | 15/100 Not PMP | 30/100 1.3>0.95 | 50/100 1.2>0.95 | 15nm Not PMP | 30nm | 50nm | 100nm |
| **AVL** | 1.25 | 1.11 | 1.06 | 96.813 | 99.267 | 99.084 | 99.389 |
| **Dekati** | 1.17 | 1.12 | 1.03 | 98.490 | 99.960 | 99.903 | 99.044 |
| **Grimm** | 1.4 | 1.19 | 1.18 | 97.143 | 98.933 | 83.299 | 74.500 |
| **Bespoke** | 1.24 | 1.09 | 1.06 | 99.899 | 99.990 | 99.996 | 99.900 |
| **CS** | 1.73 | - | 1.08 | 100.00 | 100.00 | 100.00 | 100.00 |

It may be observed that as would be expected the two commercially available VPR namely the Dekati DEED and the AVL APC400 pass all of the PMP performance criteria, as do the consortium bespoke VPR and University of Minnesota CS. However, the Grimm ESS does not conform to the volatile removal efficiency even though it does the PCRF criteria.

On looking at the values within Table 9 it may be observed that the most efficient VPR in terms of volatile removal are the University of Minnesota CS followed by the consortium bespoke VPR at 100% and 99.99%. And in terms of the PMP PCRF ratios which describe how uniform the particle losses are in the 30-100nm size range the consortium bespoke VPR and Dekati DEED have the average values closest to 1.0 then followed by AVL APC400 and Grimm EES.

This highlights that even though the commercially available VPR conform to PMP there is the opportunity to further improve on them with slight modification to the dilution and evaporation tube temperatures or inclusion of a CS as an addition or alternative to the evaporation tube.

As discussed in Section 4.4.3 gas reduction factors were calculated for the two approved commercially available PMP and with this data along with the particle reduction factors measured it was possible to calculate actual PCRF values which could be compared to the PCRF of 100 that were stated by the analysers. The data from this study is given in Table 10.

**Table 10 PMP measured versus stated PCRF for Dekati DEED and AVL APU400**

| VPR | Stated PCRF | Measured gaseous dilution ratio | Measured PMP penetration (av.30/50/100) | Real PCRF | PCRF % difference (pass <10%) |
|---|---|---|---|---|---|
| Dekati | 100 | 81 | 0.9 | 90 | 10 |
| AVL | 100 | 73 | 0.8 | 91.3 | 8.7 |

As can be seen the criteria within PMP for compliance the stated and measured PCRF must be within 10% and when calculating the actual PCRF by dividing the measured gas reduction factor by the measured penetration efficiency for the Dekati DEED and AVL APC400 they come out at 90 and 91.3 which are just within the 10% variance permitted from the PCRF of 100 which was stated. However, this variation could add extra uncertainty (±10%) to future SAE E31 Committee ARP protocols for the measurement of non-volatile number PM if similar approaches to PMP are adopted. However, it is felt that this uncertainty could be reduced (~2%) by utilising online gaseous dilution ratio measurements based on measurement techniques described in SAE ARP 1256c.

## 4.5 Volatile Sensitivity of Online Mass Measurement Analyser

Although mass measurement is a part of the PMP protocol it is simply a pass fail metric based on gravimetric principles thus there are no prescribed methods for non-volatile PM mass measurement as would be required within an SAE PM measurement ARP, therefore the consortium following discussions with the SAE E31 decided to investigate the effect of volatile PM on the measurement of mass utilising online non-volatile mass measurement instruments. It is perceived that if the mass instruments are shown to be insensitive to volatile PM then the requirement for a VPR before the SAE ARP mass measurement suite is mitigated thus removing all the uncertainties associated with the use of a VPR.

It was hoped that all three proposed instruments namely the Artium LII 300, Thermo MAAP and AVL Photo acoustic soot sensor (PASS) would be tested with pure tetracontane PM produced using the consortium condensation aerosol generator, to see if there was any interference or zero offset witnessed.

Unfortunately due to a malfunction of the pressure sensor of the AVL PASS unit prior to testing it was not possible to include this instrument in this study.

### 4.5.1 Experimental Set-up

A schematic of the experimental setup used for the investigation non-volatile mass measurement techniques to volatile PM is given in Figure 31. As can be seen the two instruments were placed downstream of the volatile generator in parallel with the AMS which gave a measure of volatile mass entering the units. Unfortunately owing to the maximum flow rate of the volatile generator being 10 L/min the LII and MAAP had to be run sequentially.

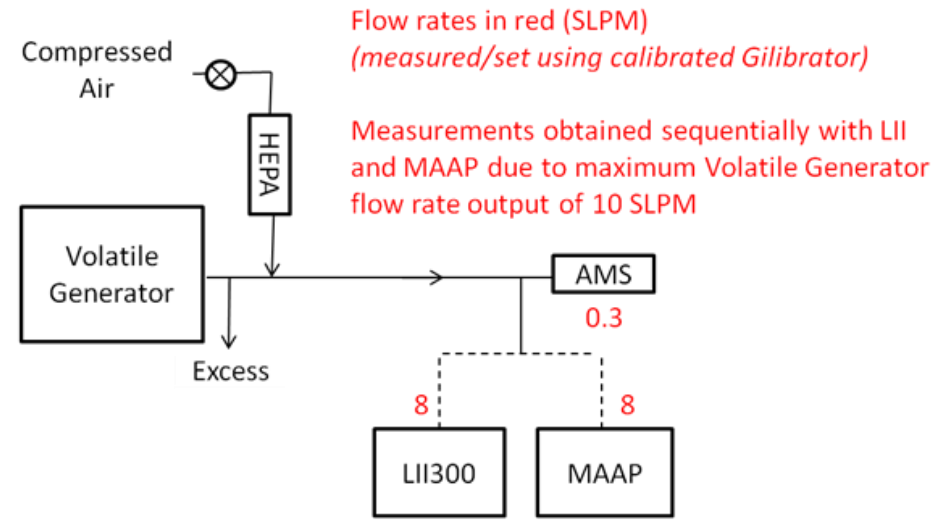


**Figure 31 Schematic representation of experimental set-up utilised to study effect of volatile PM on non-volatile mass measurement devices**

### 4.5.2 Results and Discussions

The results from the volatile sensitivity study are presented in Table 11. As can be seen there appears to be no sensitivity of the Artium LII 300 to pure tetracontane PM at concentrations of up to 1000µg/m$^3$ as measured by the AMS. The thermo MAAP by contrast seems to witness a zero offset which increases with increasing volatile mass loading becoming visible at mass loadings of 480µg/m$^3$ leading to a maximum net zero offset of ~10.5µg/m$^3$ for AMS measured loadings of ~1000µg/m$^3$ which equates to a 1% zero offset.

It should be noted that although the Artium LII 300 has a lower sensitivity <2µg/m$^3$ (typically 0.5µg/m$^3$) so would be in real terms comparable to the MAAP at the lower concentrations of 30 & 150µg/m$^3$ however at higher loadings it appears to be less susceptible. As full engine certified test data taken during the SAMPLE II testing witnessed a maximum measured AMS volatile mass loading of 255µg/m$^3$ at ICAO 3 thrust levels which is of the same order of mass loadings expected for non-volatile mass which is typically in the 50-1000 µg/m$^3$. It is thus observed in this experimental set-up that both the Artium LII 300 and Thermo MAAP instruments are unaffected by the expected levels of volatile PM witnessed in modern full scale civil aviation gas turbine engines. However, this experiment only investigated the effect of pure volatile on mass instruments thus does not ensure that the instruments are unaffected in a mixed aerosol containing volatile coated carbonaceous soot.

**Table 11 Sensitivity of non-volatile mass measurement analysers to pure volatile tetracontane PM**

| | Concentration measurements (µg/m$^3$) | | | | |
|---|---|---|---|---|---|
| **Volatile loading (AMS)** | 0 (background) | 30 | 150 | 480 | ~1000 |
| **LII** | 0 | 0 | 0 | 0 | 0 |
| **MAAP** | 0.21 | 0.19 | 0.32 | 1.4 | 10.5 |

## 4.6 VPR Appraisal using Combustor Rig and Hot End Simulator (HES)

### 4.6.1 Description of Combustor Rig and Hot End Simulator

The facility used to provide PM / exhaust gas was the GTRC combustor and Hot End Simulator (HES) rig. This facility has been used in previous SAMPLE and SAMPLE II testing campaigns and further details can be found in the associated reports.

The facility upstream of the rig under consideration comprises of the main air handing and treatment hardware. Air is introduced to the combustion chamber pre-heated and at the required mass flow. Pressure is controlled on the experiment, usually by a back-pressurising valve, but in the case of this experiment a choke-plate downstream of the combustor maintained the operating pressure (as described later). A compressor transfers the incoming air into a gas-fired non-vitiating heater, where it is raised to the required temperature for the test. The mass flow rate is measured using a coriolis meter, located upstream of the rig test section.

The rig conditions are monitored and controlled from a control room, which is remote from the rig room for the purposes of safety. The operators have full control over all of the operating parameters in the experiment using a computer controlled Supervisory Control & Data Acquisition (SCADA) system. Rig and plant conditions are logged once per minute and stored on the instrumentation and logging systems in the control room. This room also houses the gas analysis apparatus.

An overall schematic of the combustion rig and HES is shown in Figure 32 and a photograph is shown in Figure 33. These diagrams show the assembly of the rig, with locations of the combustion section, HES and exhaust gas sampling probes. The flow in the process is from left to right; pressurised, heated air is supplied to the combustion can where fuel is injected and burnt at constant pressure. The pressure in the combustion can was maintained by a choke plate, which is a matrix of holes in a water-cooled assembly that holds the pressure in the upstream section.

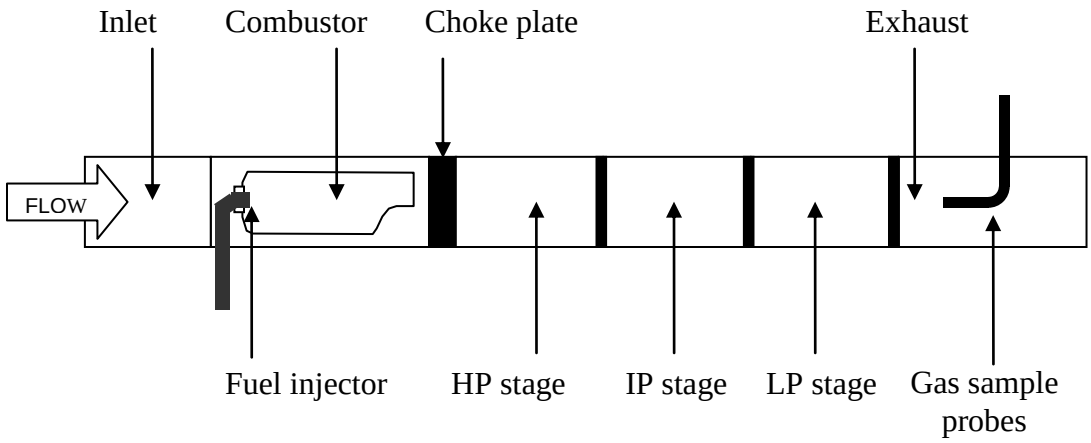


**Figure 32 Schematic of the combustion system, HES and location of gas sampling probes.**

For the combustion section of the rig, an aerospace cannular combustion chamber, constructed out of transpiration cooled steel was used for the tests. Fuel was provided into the can via an air-blast atomiser, a modified version of the type used in an engine configuration. The fuel used in this trial was aviation grade kerosene, known as Jet 'A'.

The HES is a facility that sits behind the combustor, mimicking the behaviour of a turbine section in a gas turbine. This component reduces the pressure and temperature of the exhaust gases by removing heat rather than work from the exhaust gases. The HES is comprised of three separate heat exchanger stages. Each stage simulates the rotor workload while variation of the cross-sectional area and trim plates simulates the pressure stages in each consecutive turbine, referred to here as the high, intermediate and low pressure stages. Pressure was maintained in these sections via pressure trim plates, similar to the upstream choke plate, consisting of a matrix of holes, designating the effective blockage ratio.

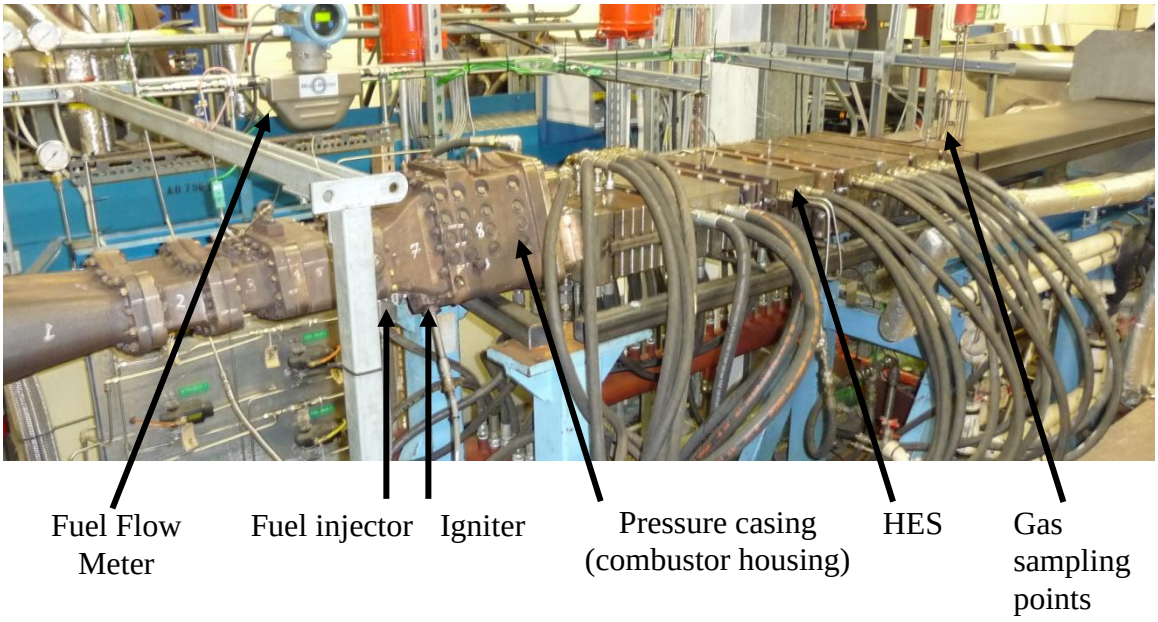


**Figure 33 Photograph of the combustor, HES and gas sampling point.**

For the purposes of this experimental campaign the combustor and HES were used to provide a standard smoke source for the experimental programme. The location of the gas sample probes was such that they were under only a slight positive static pressure of ~1.05 bar plus additional dynamic pressure from the flow of the gas stream. For this reason the sample was either extracted by the suction provided by an ejector dilutor or by pumps positioned downstream of the measurement instruments.

### 4.6.2 Sampling system and Analysers used

The gas sample was conveyed to the VPR and instrument suite using a bespoke transport system designed and constructed from trace heated stainless steel seamless tube (ID=7.75mm) coupled with a bespoke stainless steel heat exchanger with internal diameter equal that of the sample line, which is shown schematically in Figure 34.

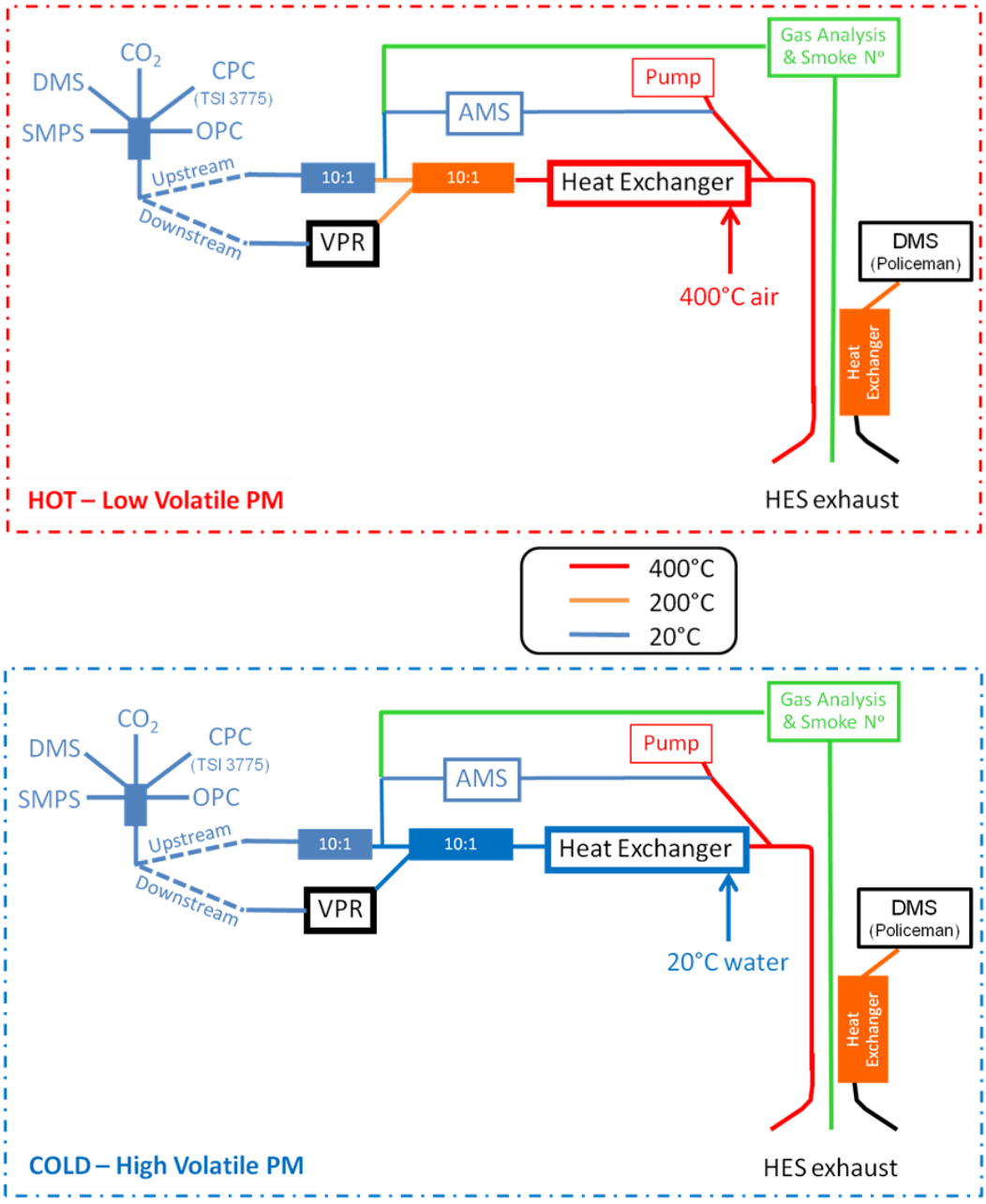


**Figure 34 Schematic of sampling system designed to offer high and low levels of volatile PM from the HES**

As can be seen there is a 3 point probe positioned in the HES exhaust similar to that used in the HES testing of the SAMPLE II test campaign. Each of the three ports supply sample to the test VPR / instrument suite, gas analysers and 'policeman' DMS respectively. The lines supplying the gas analysis and policeman DMS are maintained constant for the duration of the entire test campaign ensuring uniformity of results. However, it should be observed the PM test line can be changed from a HOT- low volatile PM condition to a COLD- high volatile PM condition by changing the temperature of the integral heat exchanger from 400°C (air heated) to 20°C (water cooled), along with changing the primary diluter and corresponding diluent temperature from 200°C to 20°C.

The theory behind each configuration is as follows:

***HOT- Low Volatile PM Configuration:-***

> The heated sample lines and heat exchanger at 400°C keep the volatile fraction in the gaseous phase up to the primary point of dilution whereby the hot (200°C) diluent rapidly dilutes the exhaust and ejects a large portion of the volatile fraction thus suppressing condensation of the gas phase volatile into volatile PM before entry to the VPR.

***Cold- High Volatile PM Configuration:-***

> The heated sample lines at 400°C keep the volatile fraction in the gaseous phase up to the heat exchanger whereby rapid cooling to 20°C causes the gaseous volatile to drop under the saturation point and condense out as volatile PM. At the primary point of dilution the cold diluent rapidly dilutes the exhaust and owing to the cold environment the volatile PM does not re-evaporate before entry to the VPR.

Independent of which condition is chosen, the sample travels through the same sample train namely heated line, heat exchanger, primary diluter, however at this point the sample train splits to allow for measurement upstream and downstream of the VPR under test (shown by dashed blue line in Figure 34) by using flexible conductive tubing. It can be seen that measurements measured upstream of the VPR had an extra diluter in series; this was to ensure that upstream CPC measurements were conducted in single count mode. The secondary diluter used was a PALAS VKL-10E for the commercial VPR measurements, however, as this device was required as part of the consortium bespoke VPR whilst testing the bespoke unit this was exchanged with a PALAS VKL-10.

Unfortunately the consortium did not have duplicate analysers to allow simultaneous upstream and downstream measurement of the VPR so sequential measurements were made and these were then normalised against each other by using the ‘policeman’ DMS data.

A photograph showing the sample line used during VPR characterisation using the HES is given in Figure 35. As can be seen the aforementioned instrument suite could not easily be moved to sit either upstream or downstream of the VPR under as such the instrument suite stayed at one location and flexible conductive silicon tubing was used to connect to either upstream or downstream.

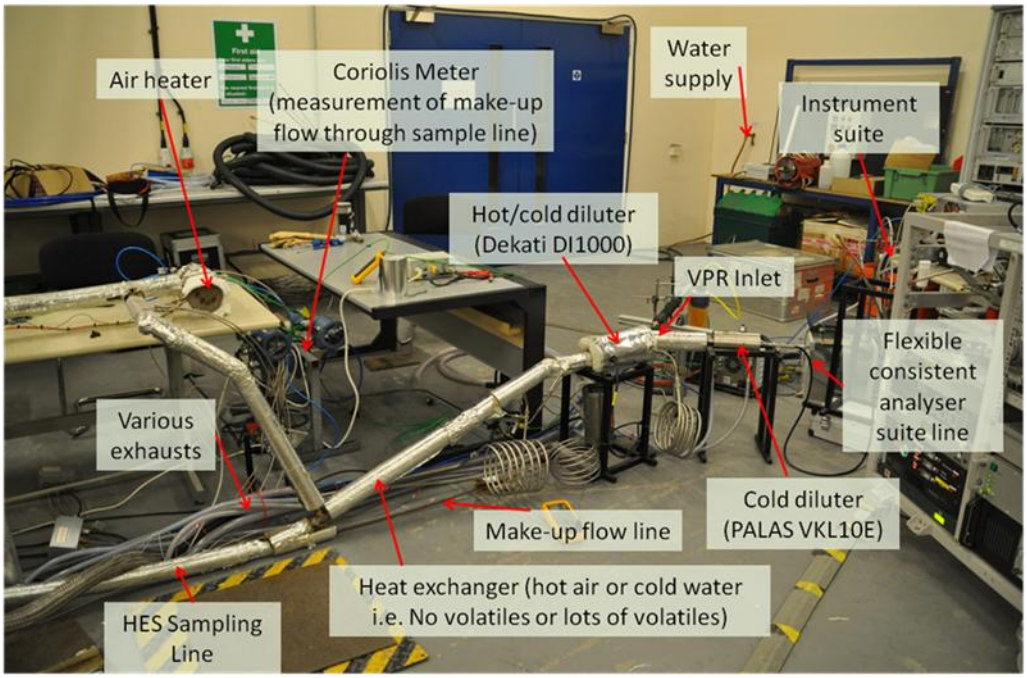


**Figure 35 Photograph of sampling line setup utilised for VPR appraisal using HES**

A list of the analysers used for the VPR characterisation is given below in Table 12 and shown photographically in Figure 36. Descriptions of the instruments are given in detail in both the SAMPLE & SAMPLE II reports so will not be discussed further at this time.

**Table 12 Instruments used for measurement of PM in the study.**

| Equipment | Acronym | Measurements |
|---|---|---|
| **Richard Oliver Smoke Meter** | SN | Smoke Number |
| **Aerosol Mass Spectrometer** | AMS | Volatile PM |
| **Differential Mobility Spectrometer** | DMS | Size and number |
| **Multi Angle Absorption Photometer** | MAAP | Mass |
| **Optical Particle Counter** | OPC | Number |
| **Condensation Particle Counter** | CPC | Number |
| **Scanning Mobility Particle Sizer** | SMPS | Size and number |
| **Gas Analysis** | GA | CO, $CO_2$,THC, $NO_x$, $O_2$ |

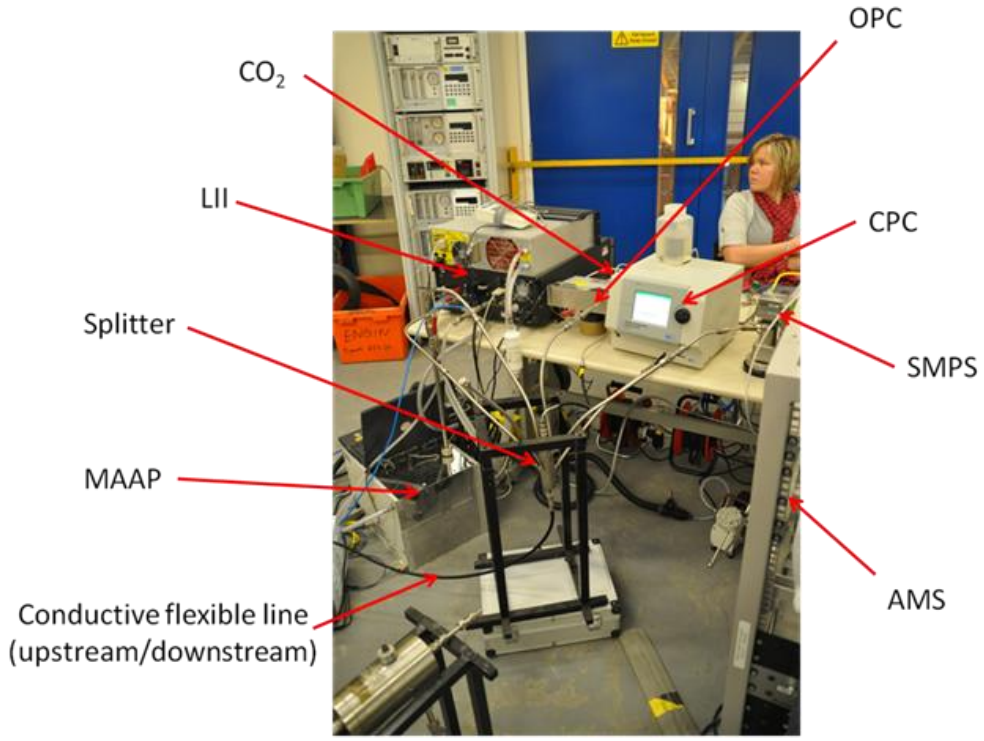


**Figure 36 Photograph of instrumentation suite used for characterisation of the VPR during HES trials**

### 4.6.3 Results & Discussions of Combustor Rig and Hot End Simulator

It was hoped that the three commercially available VPR (Dekati DEED, AVL APC400 & Grimm ESS) would be tested during the HES test phase. However unfortunately, the consortium were not able to have access to the AVL European demonstration unit during the HES testing phase, thus during the HES test campaign the Dekati DEED, Grimm ESS and consortium bespoke VPR were tested.

Size distributions and total number concentrations were taken upstream and downstream of the VPR utilising both DMS ,SMPS and CPC, as explained a 'policeman' DMS was ensuring the sequential experiments performed for the VPR were not affected by HES variation with variations witnessed typically <3% per size bin for subsequent experiments however, large deviations of tens of percent (thought to occur because the HES was purposely run off its combustor line to increase volatile production) were witnessed day to day making inter experiment comparisons difficult thus only subsequent tests for number concentration of a particular VPR have been normalised with size distribution normalisation appraised and discussed later. Inter day VPR normalisation was not performed as it was thought that this approach could bring about large uncertainty in any data presented. Unfortunately due to the mass flow control dilution employed in the Grimm ESS unit it is not possible to run the DMS as its flow rate requirement of 8L/min would only permit a lower than 1 times dilution ratio to be achieved, thus DMS was only conducted with the Dekati DEED and consortium bespoke VPR.

### 4.6.3.1 Size Distribution Data for HES test

As stated earlier it was not possible to derive DMS data for the Grimm ESS however, due to the lower flow rates required by the SMPS a size distribution could be derived for the Grimm ESS and this is presented as a log normal plot in Figure 37.

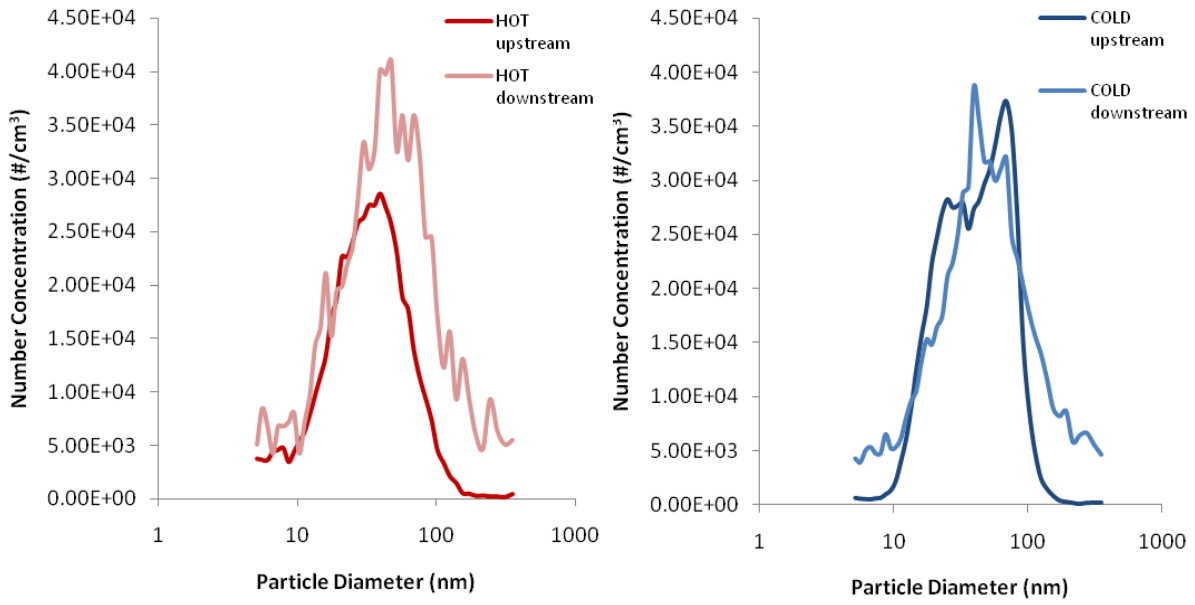


**Figure 37 SMPS size distributions of PM upstream and downstream of the GRIMM ESS during HOT and COLD sample line configuration**

It should be highlighted that there appears to be a growth of particles within the Grimm ESS on the HOT configuration with higher number counts and a larger mean diameter being witnessed downstream of the Grimm ESS, the increase in PM witnessed for the HOT case may be due to the relatively low max temperature (200°C) and lack of evaporation tube which allows nucleation of the volatile fraction which was purposely held in the vapour phase prior to entry to the VPR to nucleate and condense out during transport through the Grimm ESS unit.

In the COLD configuration however, as would be expected there appears to be a small nucleation mode peak at approximately 20nm. This peak is what was intended to be produced in this COLD configuration.

On reviewing this data, during the HES test, it was felt that as the remaining VPR to be subsequently tested on the following days were more capable in volatile removal (Figure 26) that an exhaust containing higher levels of volatiles should be sought. For this reason a new engine condition with even higher volatile loadings was found by driving the HES to a richer cooler condition (off the combustor line). A new higher volatile loading condition was found and this is what the Dekati DEED and consortium bespoke VPR were tested on as discussed later.

Size distributions for the Dekati DEED were taken using both DMS and SMPS and are presented as log normal distributions for both the HOT and COLD configurations in Figure 38 & Figure 39 respectively.

It can be seen there are very different upstream size signatures witnessed for the HOT and COLD sample line configurations with the expected very pronounced nucleation mode peak being witnessed for the COLD case. However, the DMS data (Figure 38) for the HOT case also displays a bimodal distribution before and after the VPR which suggests that the nucleation mode peak (at 15nm) contains volatile and non-volatile particles as was witnessed in SAMPLE & SAMPLE II HES and engine data. It can be seen in all four plots that the VPR appears to reduce number concentrations across the whole size distribution with larger reductions witnessed in the COLD cases as would be expected with higher levels of PM in the original sample. However, corrections are not made for an average PCRF for the size distributions as to apply an average PCRF as is done in PMP could give misleading affects to the size distributions knowing that penetration efficiency is dependent on particle diameter with higher losses being witnessed at lower sizes (Figure 24) thus suppressing the actual magnitude of the primary nucleation peak (<30nm).

In the COLD configuration DMS plots are presented at conditions of high levels of condensed volatile entering the VPR. At this condition there appears to be a reduction and increase in size of the primary nucleation peak whilst there is a decrease and shrinkage of the secondary accumulation mode, this implies that there is removal of pure volatile PM from the nucleation mode and evaporation of volatile coating from the accumulation mode PM.

An example of the effective drift of the HES as a smoke source is also included for comparison in the DMS HOT plot (Figure 38). As can be seen a downstream plot normalised for HES drift is plotted against a non-normalised plot (dashed line). It is noted that the two downstream plots are very similar and as these plots are being used qualitatively rather than quantitatively in this study that normalisation of the subsequent data was not required.

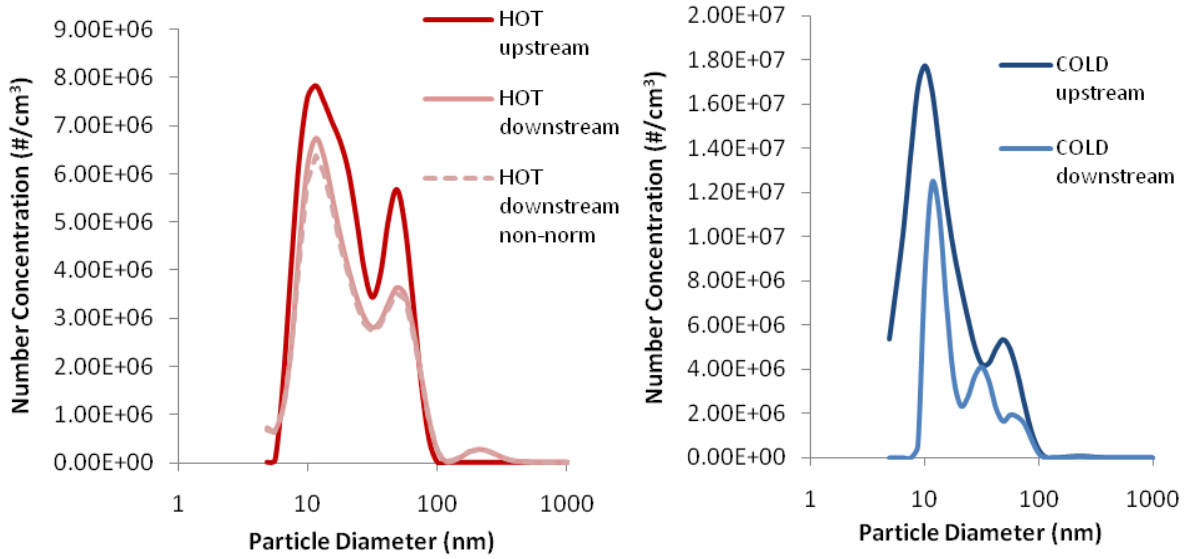


**Figure 38 DMS size distributions of PM upstream and downstream of the Dekati DEED during HOT and COLD sample line configuration**

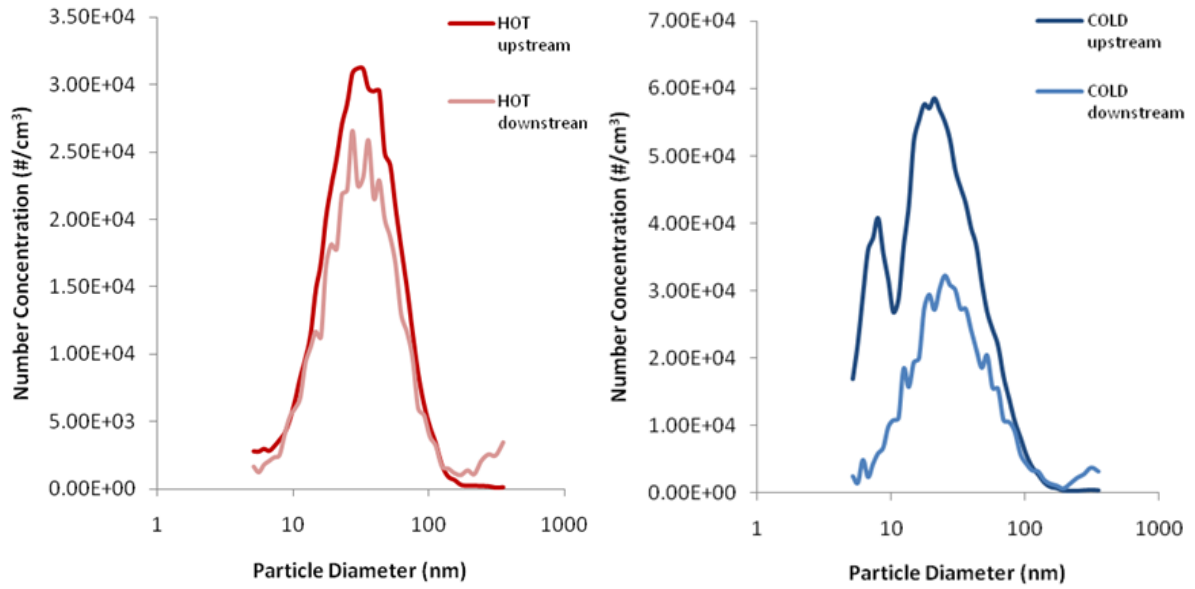


**Figure 39 SMPS size distributions of PM upstream and downstream of the Dekati DEED during HOT and COLD sample line configuration**

DMS and SMPS plots for the consortium bespoke VPR are presented in Figure 40 and Figure 41 respectively. Once again it can be seen that in all four plots there is a reduction in PM across the complete size range. The major difference in this data set compared to that of the Dekati DEED is the lack of the nucleation mode in the upstream SMPS data, again this highlights differences observed between DMS and SMPS data as have been observed previously in SAMPLE and SAMPLE II data.

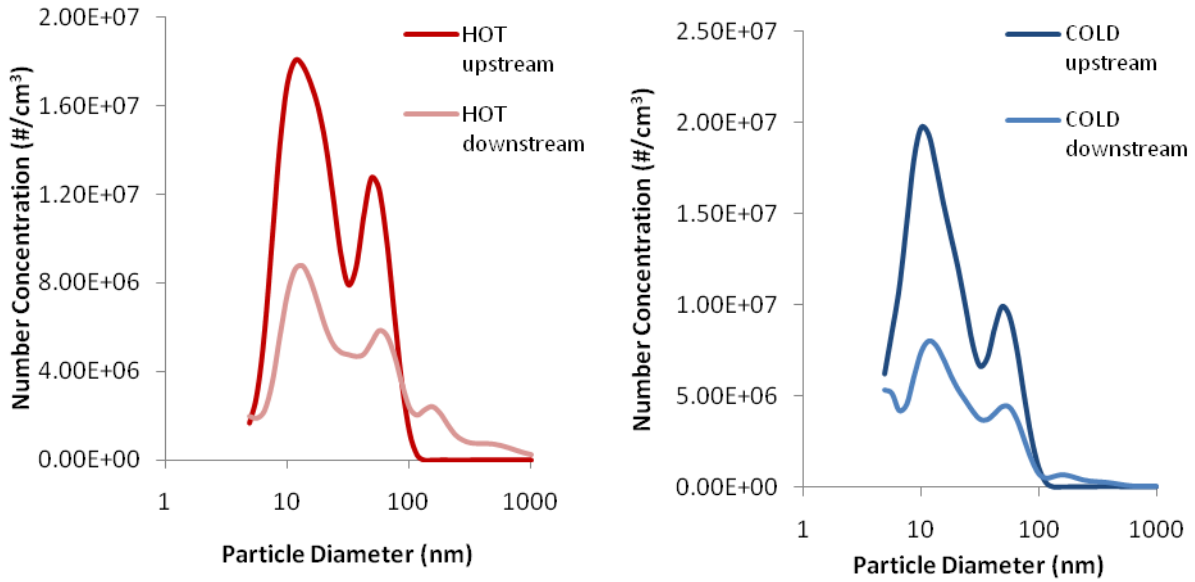


**Figure 40 DMS size distributions of PM upstream and downstream of the consortium bespoke VPR during HOT and COLD sample line configuration**

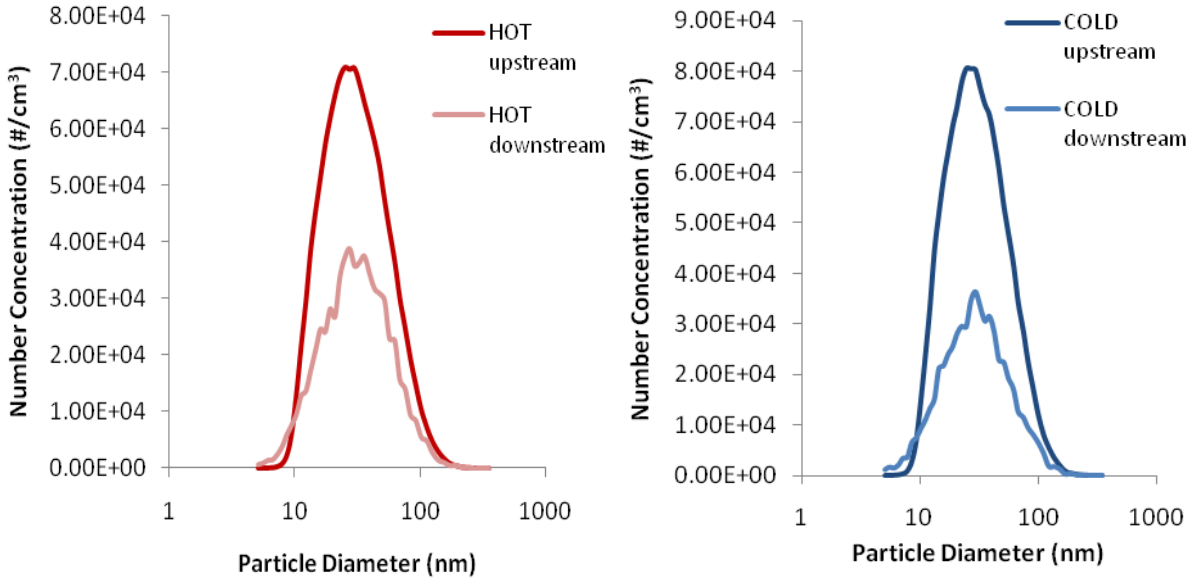


**Figure 41 SMPS size distributions of PM upstream and downstream of the consortium bespoke VPR during HOT and COLD sample line configuration**

It is noted for all of the downstream data for both the consortium and Dekati units that in the DMS data there appears to be a third large mode appearing in the data, for which the authors do not at this time have an explanation for except possible agglomeration of particles. There is also the surprising trend of reduction in number of the agglomeration mode in all the downstream measurements which even if you allow for the expected 10-20% losses associated with the measured PCRF would imply that there are some large volatile particles being removed or large numbers of small volatile coated particles being shrunk back down to nucleation mode sized solid particles.

### *4.6.3.2 Number Concentration Data for HES test*

The number concentration data measured using a TSI 3776 CPC ($D_{50}$=7nm) is presented in Table 13 for the three VPR tested. As discussed earlier and illustrated in Figure 34 the CPC was sequentially positioned upstream and downstream of the VPR. In both configurations the CPC was downstream of a primary diluter, and depending on configuration either an additional secondary diluter or the VPR under test was positioned in line. As such the data presented is corrected for the relevant dilution ratio stages and the individual average VPR PMP PCRF calculated in Section 4.4 along with any rig fluctuations witnessed using the 'policeman' DMS.

**Table 13 Number concentration data for VPR validation tests performed on the HES**

| VPR | Sample Condition | Number Concentration (#/cm$^3$) | | Volatile Particles removed |
|---|---|---|---|---|
| | | Upstream | Downstream | |
| Dekati | Hot | 9.98E+06 | 6.38E+06 | 36% |
| | Cold | 4.85E+07 | 1.04E+07 | 78% |
| Grimm | Hot | 7.57E+06 | 8.49E+06 | -10.8% |
| | Cold | 8.41E+06 | 7.65E+06 | 9% |
| Consortium Bespoke | Hot | 1.61E+07 | 9.92E+06 | 38% |
| | Cold | 2.01E+07 | 9.73E+06 | 52% |

As can be seen it appears that the experimental configurations designed to give high and low levels of volatile PM appear to have worked with upstream values measured in the COLD high volatile PM loading configuration being noticeably higher in each of the 3 experiments.

As explained earlier the downstream measurements were corrected for PCRF so any observed differences between the upstream and downstream values can be assumed to be caused by the removal of volatile PM. Thus by comparing the differences in upstream and downstream number concentrations it is possible to determine the percentage of particles that are volatile. These values are quoted for each of the 3 VPR. As can be seen for the Dekati DEED and Consortium bespoke VPR it appears to remove approximately 37% number of the volatile PM for the low volatile HOT configuration and 78% and 52% respectively for the high COLD configuration case. As discussed earlier a different diluter was used prior to the upstream measurement for the bespoke and Dekati tests hence it is hard to compare actual numbers but both consistently show they are removing large quantities of volatile PM with more being removed the higher the fraction in the raw sample.

It is witnessed that the Grimm ESS does not seem as effective in removing volatile fraction with a 10% increase in volatile PM seen in the HOT low volatile PM configuration, and only a 9% reduction for the COLD high volatile PM case. As discussed earlier this observation may be attributed to the low temperatures and lack of evaporation tube within the unit. The lower comparable losses witnessed for the high volatile PM COLD case are also not surprising when considering the units poor performance in the PMP volatile removal efficiency experiments (Figure 26).

#### *4.6.3.3 AMS organic mass loadings for HOT and COLD HES sampling configurations*

AMS measurements were obtained as part of the HES testing to quantitatively measure in real-time for the organic (volatile) mass fraction of the sample entering the VPR under test. Unfortunately due to the sensitivity limit for the AMS (1µg/m$^3$) volatile removal efficiencies were not able to be measured downstream of the VPR. The average organic mass loading and associated standard deviation for each sampling configuration is shown below inTable 14.

**Table 14 AMS mass loadings during HES trials**

| Sampling configuration | Organic Mass Loading (dilution corrected) | |
|---|---|---|
| | µg/m3 | σ |
| HOT sample line configuration | 22 | 3.9 |
| COLD sample line configuration | 73 | 4.8 |

AMS organic mass spectra for each sampling configuration are shown below in Figure 42. Unexpectedly the fragmentation peak fingerprint is different between the sampling configurations. The source of this difference is currently unknown, however, when the peaks are compared to previous HES testing under SAMPLE II with Annex 16 methodology (undiluted 160°C) it is found that they are similar to the HOT sampling configuration. Thus the authors' hypothesis is that the COLD sampling configuration difference is due to the presence of light aerosol hydrocarbons at ambient sampling temperatures which would usually be in the gas-phase at 160°C but have condensed and coated the soot particles.

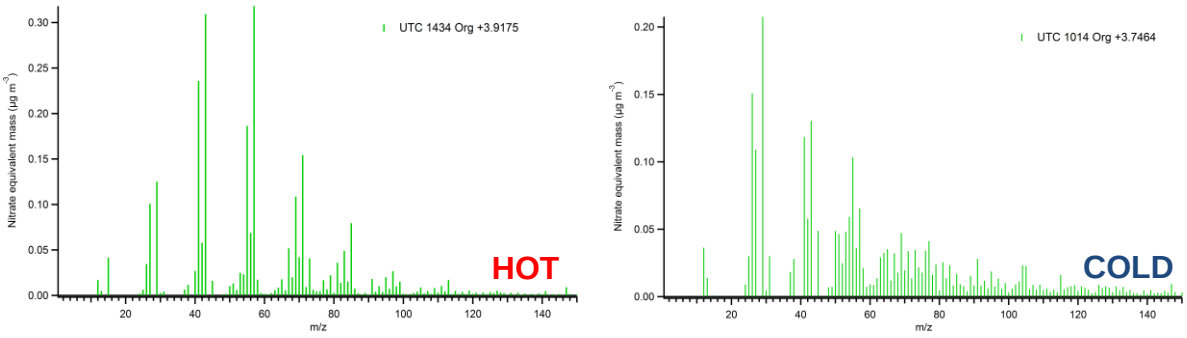


**Figure 42 AMS organic mass spectra for HES HOT & COLD sample line configuration**

## 4.7 VPR Appraisal using Full Scale Rolls-Royce Artouste Auxiliary Power Unit engine

As explained earlier the AVL APC400 was not available for trial on the HES for this reason it was decided to source an AVL APC400 for the APU engine test and trial this along with the consortium bespoke unit. In order to try and have a comparable setup to that used in the HES testing described in Section 4.6 a modification was made to the sample lines used for the full engine APU test which is described in detail later in this report (Section 6).

### 4.7.1 Description of APU Test Facility

Details of the test facilities utilised can be found in section 6.2.1 which describes the test set up which this study was run as a 'piggyback' exercise. Thus further details are not presented at this time.

### 4.7.2 Sampling system

As mentioned earlier this study was conducted as a 'piggy' back of the APU full engine test as such the SAE E31 Committee concept sampling line discussed later in section 6.2.2 was removed and replaced with a bespoke sampling system comparable but not identical to that used in the COLD HES configuration discussed earlier in Section 4.6.2.

A schematic of the configuration used is given in Figure 43. As can be seen the sampling system for VPR testing was fitted onto the end of the 6.5m stainless steel line used for the full scale APU engine testing. It consisted of a cold water fed tube in shell full bore heat exchanger similar to that used in the HES test sample line. The output of this heat exchanger then fed into the Dekati DI1000 ejector diluter which was run using 20°C Nitrogen as a diluent, the sample was then fed down short unheated stainless steel lines through some 30° splitters to the 3 VPR being tested namely the consortium bespoke VPR, an AVL APC 400 and a University of Minnesota CS all of which are discussed in detail in section 4.2.

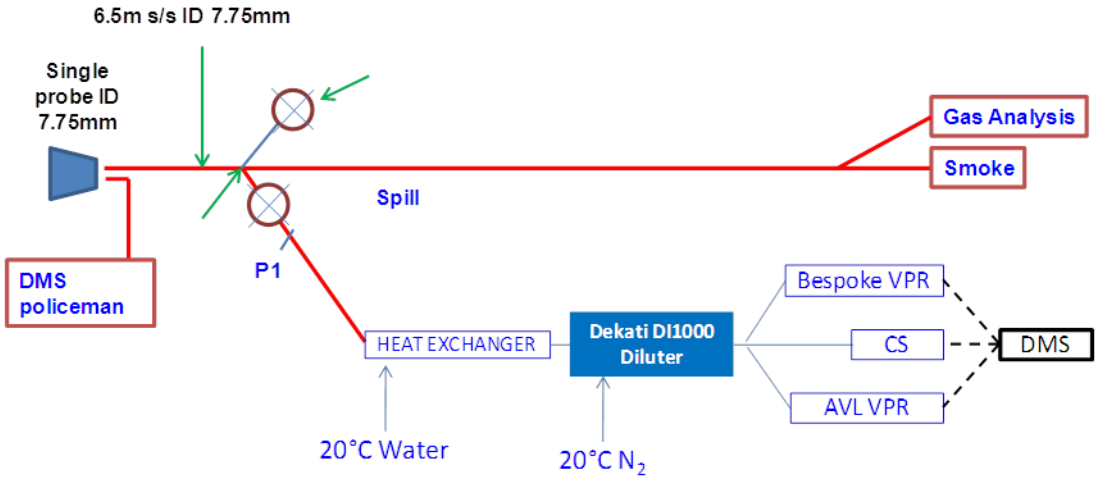


**Figure 43 Schematic representation of sample line set up used for VPR appraisal at full scale APU engine test**

### 4.7.3 Results and Discussions

The DMS results for each of the VPR (including CS) are given in Figure 44. As can be seen once again it appears that volatile PM is removed from across the entire size range of the PM. It is also observed that the CS is the most effective in removing volatile PM followed by the AVL APC400 and finally the bespoke unit if only considering the primary nucleation mode, which is a different finding to that witnessed in the PMP approach volatile removal efficiency tests which saw the AVL APC400 the least capable.

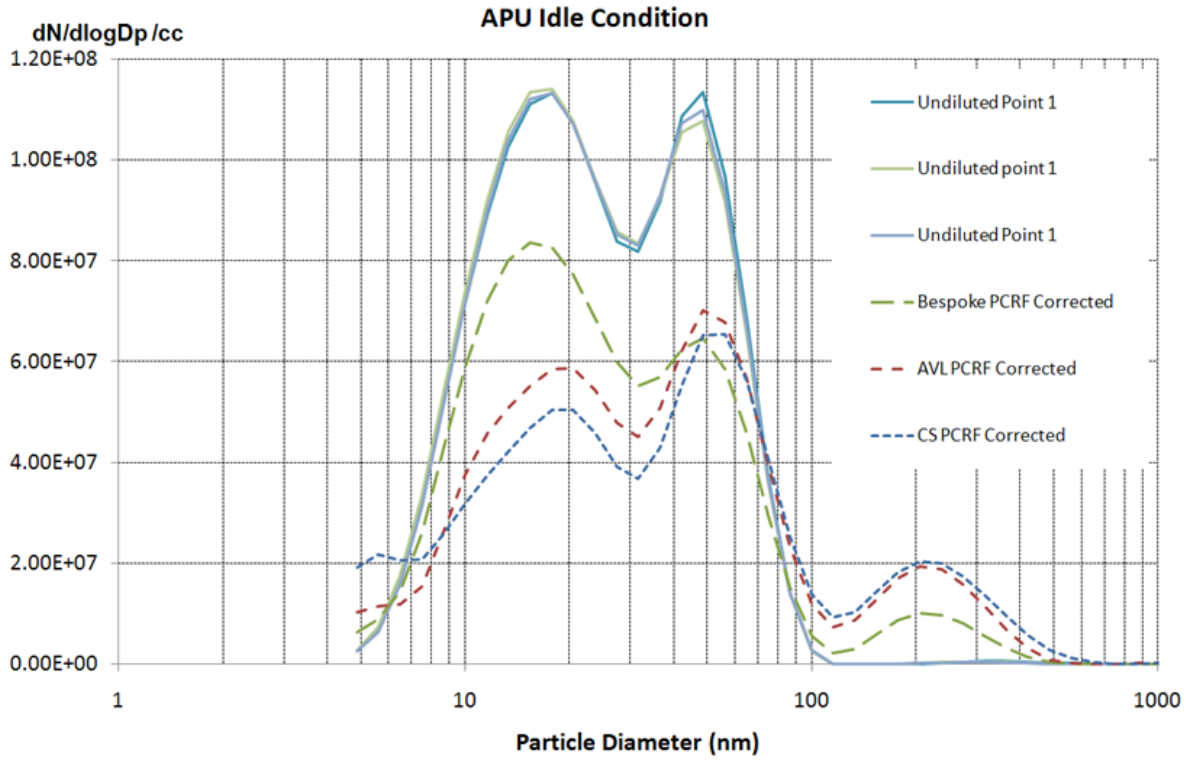


**Figure 44 VPR validation test using full scale APU engine**

However, on closer inspection of the secondary and tertiary accumulation modes it appears that the consortium bespoke unit could be shrinking more of the larger coated particles releasing smaller solid particles that may have been nucleation points which may now be counted as smaller particles which would account for the higher primary mode witnessed.

It is also observed that the bespoke unit shrinks the nucleation mode to a smaller size compared with the other two VPR. It is noted that after all VPR there are numerous particles still present in the 10-20nm nucleation mode again strengthening the hypothesis that there are large numbers of solid particles in this size range.

## 4.8 Conclusions of Task 1

1. As expected the PMP approved commercially available VPR (Dekati DEED, AVL APC400) as well as the bespoke consortium designed conform to PMP protocol in terms of laboratory based testing.
2. The Grimm ESS VPR did not meet all of the specifications set out by the PMP, it is thought that the reason for this is the lack of evaporation tube and lower temperatures utilised by the unit.
3. It was found that PMP VPR do not 'remove' all of the volatile PM but shrink over 99% of the volatile PM to a size below the 23nm cut off selected by PMP. As discussed earlier this could lead to large uncertainties particularly if the volatile to non-volatile PM number ratio is high.
4. Catalytic Stripper technology appeared to completely remove tetracontane and lubrication oil in the form of pure volatile PM and volatile coated carbon particles and would pass PMP VPR performance specifications although it does not conform to PMP design specification.
5. Data suggests that PMP type diluters could be 'slightly' modified to potentially reduce the attainable lower size cut-off by increasing the primary dilution temperature along with the evaporation tube temperature.
6. It was witnessed during numerous combustor and full scale engine tests that volatile particles appear to exist throughout the measureable PM size range, and are not only present in the primary nucleation mode peak as current scientific understanding would suggest.
7. Online non-volatile PM mass measuring instruments (MAAP & LII) are insensitive to PMP approach tetracontane volatiles at loadings representative of modern large scale gas turbine engines (as witnessed in SAMPLE II Rolls-Royce full-scale engine test).
8. It is thought that a reduction in uncertainty could be gained by not using a PMP type PCRF which includes the preset dilution ratio, by including an online gaseous measurement to calculate the actual dilution ratio witnessed during testing which has been shown to be sensitive to fluctuation in sample line pressure.

# 5. Task 2: Design and Manufacture of Sampling System.

## 5.1 Introduction

The entire measurement system for non-volatile particulates from a gas turbine exhaust is shown as a flowchart in Figure 45. The flowchart breaks down each part of the system and categorises the portions into three elements; Collection, Transfer and Measurement.

The collection section which includes the particle transfer system from probe inlet to splitter 1 inlet (comprising of 1PTS and 2PTS) as shown in Figure 45, has been agreed by the SAE E31 Committee and regulators (SAE E31 PM Sub-committee meeting at Cardiff 2010) to conform to existing Annex 16 specifications and therefore existing probe/rake hardware. In order to take full advantage of the benefit to dilute the sample as early as possible (to prevent particle coagulation and keep the length of the standardised Transfer section as a maximum to minimise line loss uncertainties), based upon existing aircraft engine manufacturer hardware specifications the residence time for the Collection portion has been set at a maximum of 3 seconds and the length of 2PTS to <8m. As the Collection section is based upon engine manufacturer/engine type/engine size, detailed required specification/definition is not given in this report.

The Measurement section (comprising of nvPNi and NVPMi) contains the instruments to measure non-volatile mass and number. As these instruments are commercially available, detailed required specification/definition is not given in this report.

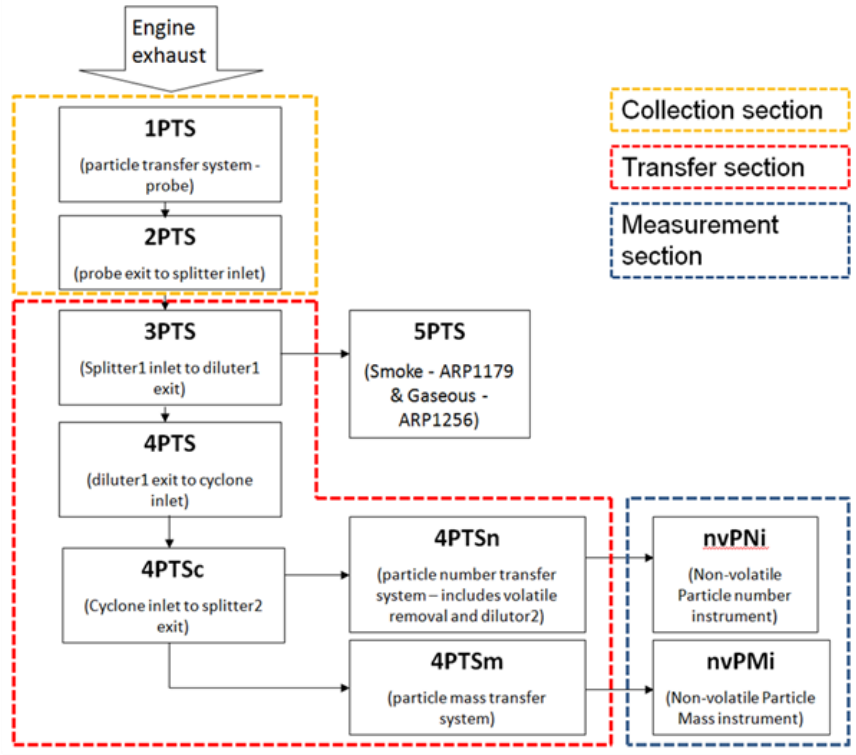


**Figure 45 Flow chart of SAE E31 Committee concept non-volatile sample line supplying the mass and number measurement suites**

## 5.2 Proposed Transfer System Design

The design of the proposed sampling system used in this study and that of the SAE E31 Committee was based upon results, understanding and experience gained from previous SAMPLE and SAMPLE II projects and from discussions and results presented within SAE E31 PM Sub-committee. The majority of the components including the eductor dilutor methodology were successfully demonstrated on both a rig and a large scale full engine test in SAMPLE II and subsequent full scale tests at AAFEX II which is why a nominally identical sampling system was adopted by the SAE E31 Sampling team for the SAE E31 Committee proposed system in the annual general meeting held in Ottawa 2011.

The diagram below (Figure 46) shows a simplistic diagram of the proposed sampling system used in this study and the location of the proposed measurement suites. Simplistic set-ups of the proposed mass and number measurement suites are also given in Figure 47. A full cutting list of components and reasoning for use are discussed in detail below and are presented in Table 15 & Table 19.

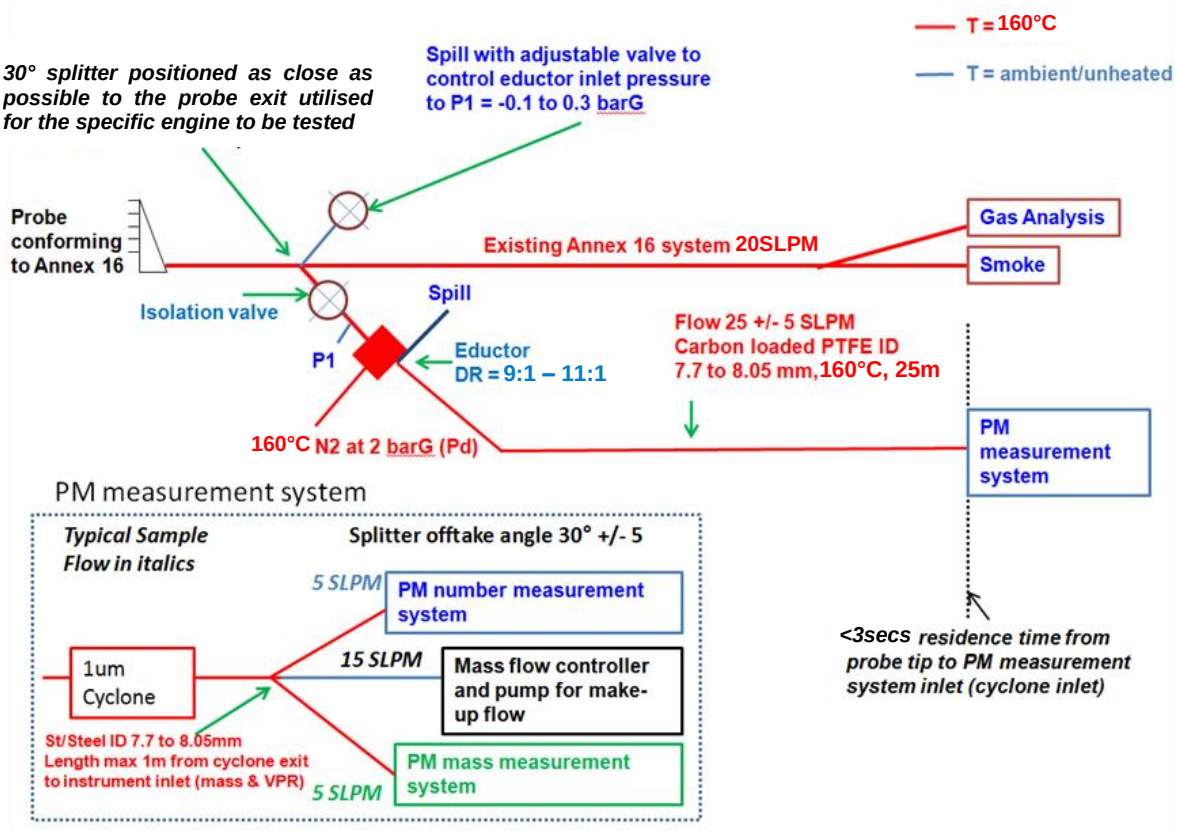


**Figure 46 Proposed non-volatile sampling system utilised in this study**

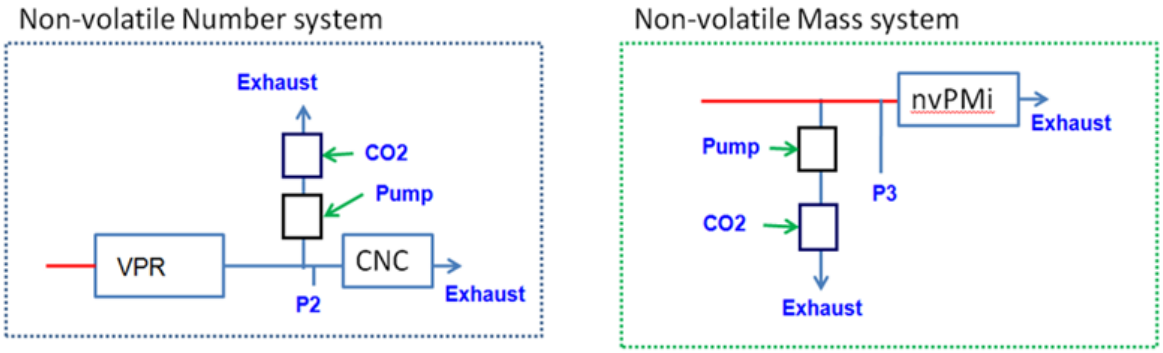


**Figure 47 Schematic representation of consortium mass and number measurement suites**

Table 15 below describes in detail the design specifications of each component of the transfer system built by the consortium for use in full scale engine testing.

**Table 15 Consortium built transfer sampling system specifications**

| Section | Component | Description | Specification |
|---|---|---|---|
| ALL | Fittings | To join system components together | Stainless steel /Inconel material<br>Smooth bore, no shoulders |
| | All lines | To transport PM sample with minimum particle losses. | Sampling lines shall be as "straight through" as possible. Any necessary bends shall have radii which are greater than 10 times the inside diameter of the lines. |
| 3PTS | Splitter 1 | To split the exhaust sample with minimal particle loss between<br>1) Allowing pressure relief from existing Annex 16 line (Smoke and Gaseous)<br>2) Existing Annex 16 line and PM line.<br>This can consist of either a single 3-branch splitter or two 2-branch splitters in series | Heated to 160 +/-15°C<br>Material: Stainless Steel<br>Angle of branch split: 30° +/- 5°<br>If two 2-branch splitters are utilised in series. The upstream splitter must be used as the pressure relief.<br>There should be no shoulder steps inside the splitter (including the attached fittings).<br>Splitter1 inlet branch ID = Inlet line ID<br>Splitter1 pressure relief branch ID >= Inlet line ID<br>Splitter1 PM branch ID = ID of diluter1 inlet<br>Splitter1 Gaseous/Smoke branch ID = Existing Annex 16 ID (4 to 8mm)<br>All branches should be kept as short as practically possible |
| | Pressure relief branch | To control and maintain near ambient sample pressure at dilutor1 inlet ($P_1$) | A suitable pressure relief valve should be used depending upon flow expected from a specific probe design across all engine thrust levels. When fully closed the pressure relief valve seal should be capable of operating at -100mbar ambient with no leakage. Alternatively an additional full-bore ball-valve may be added downstream of the relief valve to prevent leakage at sub-atmospheric test points. |

| | | | |
|---|---|---|---|
| | Dilutor1 (PM branch) | To dilute exhaust sample using eductor-type dilutor and provide a sucked hot (160°C) consistent sample flow to 4PTS. In order to perform a leak check of the existing Annex 16 line this branch must have the option to be isolated. | Pressure measurement (P1) to be made between Splitter1 outlet and diluter1 inlet.<br>Full bore (<15% shoulder step to sample line ID) isolation valve to be place between Splitter1 outlet and diluter1 inlet. The seals should be dry and heat resistant to 160 +/-15°C<br>Diluter1 body to be heated to 160 +/-15°C<br>Diluent to be heated to 160 +/-15°C and meet dilution specifications (see below)<br>Diluter1 to meet performance specifications (see below)<br>Dilution ratio to be continuously measured using $CO_2$ analyser (see 4PTSc)<br>Diluter1 exhaust should be open to ambient |
| | Gaseous and Smoke branch | Existing Annex 16 sampling methodology, to provide flowing sample from probe to splitter1 (minimum flowrate 14 SLPM) | To follow ARP1179D (Smoke) and ARP1256C (Gaseous) specifications |
| 4PTS | PM Transfer line | Transfer of PM sample from near-engine to near-instruments. In order to minimise particle losses. | Heated to 160 +/-15°C<br>Material: grounded Carbon-loaded PTFE<br>ID 7.70 to 8.05mm<br>Length 25m<br>Flow rate to be maintained between 25 +/-5 SLPM |
| 4PTSc | Cyclone | To prevent particle-shedding (i.e non-combustion generated particles) from affecting mass and number measurements. | Heated to 160 +/-15°C<br>1 micron particle size cut-off with >99% transmission efficiency for particles <300nm<br>Flow rate to be maintained between 25 +/-5 SLPM |
| | Splitter2 | To split the PM sample with minimal particle loss between<br>1) Non-volatile mass measurement<br>2) Non-volatile number measurement<br>3) Mass flow controller<br>This can consist of either a single 3-branch splitter or two 2-branch splitters in series | Heated to 160 +/-15°C<br>Material: Stainless Steel<br>Angle of branch split: 30° +/- 5°<br>If two 2-branch splitters are utilised in series. The upstream splitter must be used as the number measurement<br>There should be no shoulder steps inside the splitter (including the attached fittings).<br>Splitter2 inlet branch ID = Cyclone outlet ID<br>Splitter2 number branch ID = Inlet line ID of volatile removal system<br>Splitter2 mass branch ID = ID of nvPMi<br>Splitter2 mass flow controller branch =< Splitter2 inlet ID<br>All branches should be kept as short as practically possible |
| | Mass flow controller and pump | To maintain constant and required sample flow rate in 4PTS and 4PTSc | A suitable mass flow controller with an air-equivalent volumetric range between 0 and 20 SLPM<br>Pump capable of drawing up to 20 SLPM from -100mbarG vacuum |
| | $CO_2$ analyser | To measure online dilution ratio of diluter1 during engine testing | Analyser to adhere to ARP1256C specification. |

| | | | |
|---|---|---|---|
| 4PTSm | Mass transfer line | Transfer PM sample to non-volatile mass instrument | Heated to 160 +/-15°C<br>Material: Stainless Steel<br>ID = ID of nvPMi<br>To be kept as short as practically possible with maximum length of 1.5m |
| 4PTSn | Number transfer line | Transfer PM sample to volatile removal device for number measurement | Heated to 160 +/-15°C<br>Material: Stainless Steel<br>ID = ID of volatile removal device<br>To be kept as short as practically possible with maximum length of 1.5m |
| | Volatile removal device | Remove volatile particles for non-volatile number measurement. Methodology either via evaporation tube or catalytic stripper methodology. To include adjustable ambient dilution to provide temperature conditioned sample to nvPMi and reduce number concentration to CNC single-count range. | Suggested performance specifications based upon Task 1 (see below) |
| | $CO_2$ analyser | To measure dilution ratio after volatile removal device | Analyser to adhere to ARP1256C specification |

### 5.2.1 Eductor Performance Specifications

The consortium recommends that the eductor diluter used in the sampling system requires the following set-up and specifications:

1. A Penetration Efficiency Calibration would need to be conducted for the eductor diluter the following method is proposed by the authors:
    - Operate eductor at 10:1 +/-2 dilution ratio at ambient pressure conditions at the temperatures that unit would be run in normal operation.
    - Use a carbon or soot generator to produce size-selected aerosol (conducted with a DMA, size calibrated using traceable latex spheres) at numerous cut sizes (15, 30, 50 & 100nm) at the concentration specified in Table 16.
    - The transmission at each of the size selected aerosol should meet the minimum requirement as specified in Table 16.
2. The Inlet flow rate range should be operated at between 3 to 10 SLPM

3. Inlet sample pressure sensitivity:
    - At an inlet pressure range -100mbarG to +300mbarG dilution ratio should be controllable to dilution ratios between 5:1 & 15:1.

**Table 16 Eductor performance specification**

| Particle size selected (nm) | 15 | 30 | 50 | 100 |
|---|---|---|---|---|
| Inlet aerosol concentration required (#/cm$^3$) | >1e4 | >1e5 | >1e5 | >1e5 |
| Transmission efficiency required | >0.8 | >0.9 | >0.9 | >0.9 |

### 5.2.2 Dilution Performance Specifications

The consortium recommends that the diluent & zero grade gases used in the dilution stages and gas analysers have the following specifications:

1. Nitrogen Diluent should have following purity
    - Nitrogen 99.95% purity for diluent gas
    - Nitrogen 99.995% purity for Zero for $CO_2$ analyser

2. Dilution Ratio measurements using $CO_2$ analysers to ARP1256c performance specifications given below:
    - Zero Drift: less than 1% in 1 hour
    - Span Drift: less than 1% in 1 hour
    - Linearity: < ±1% Full Scale
    - Noise: less than ±1% Full Scale
    - Resolution: Better than ±0.5%
    - Precision: Better than ±1% Full Scale

3. $CO_2$ analyser should have suitable range
    - <5000 ppm with span gas >90% of range used.

### 5.2.3 Volatile removal device (VPR) Performance Specifications

The consortium recommends that the VPR used in the sampling system requires the following set-up and specifications:

1. A Transmission efficiency calibration would need to be conducted for the VPR the following method is proposed by the authors:
    - Operate VPR device with CNC, Use a carbon or soot generator to produce size-selected aerosol (conducted with a DMA, size calibrated using traceable latex spheres) at numerous cut sizes (15, 30, 50 & 100nm) at the concentration specified in Table 17.
    - The transmission at each of the size selected aerosol should meet the minimum requirement as specified in Table 17.

**Table 17 VPR transmission efficiency calibration specification**

| Size selected (nm) | 15 | 30 | 50 | 100 |
|---|---|---|---|---|
| Inlet aerosol concentration required (#/cm$^3$) | >1e4 | >1e5 | >1e5 | >1e5 |
| Transmission efficiency required | >0.5 | >0.7 | >0.7 | >0.7 |

2. A Volatile removal calibration would need to be conducted for the VPR. The consortium believes that there is insufficient evidence available to set this specification at this time but believe that the approach adopted by PMP may not be suitable for aero type testing. As a 99% volatile particle removal efficiency only tested with pure volatile PM (as defined by PMP) may introduce an intolerable uncertainty as discussed earlier when measuring mixed aerosol. Table 18 gives suggested concentrations and removal efficiencies but is based on a very limited data set presented earlier in section 4.

**Table 18 Volatile remover calibration specifications**

| Size selected (nm) | 15 | 30 | 50 | 100 |
|---|---|---|---|---|
| Inlet aerosol concentration required (#/cm$^3$) | >1e4 | >1e5 | >1e5 | >1e5 |
| Volatile removal efficiency | >99.5% | >99.5% | >99.5% | >99.5% |

### 5.2.4 Cyclone performance specifications

The cut-off diameter ($d_{50}$) or size selection of a cyclone is regulated by the sample air flow rate, the diameter of the inlet nozzle or jet, the inner cylinder diameter and exit tube diameter. To a small degree the grit pot dimensions also affect performance. The theoretical design and parameters of a cyclone are complicated and therefore cyclones fall into two categories, the historic Stairmand (pre-computer design) and modern Sharp Cut Cyclone (SCC) designs modelled by UK Health & Safety Lab (HSL) and BGI Inc. Using modern computer models, a numerical empirical analysis can calculate critical physical dimensions and cut-point at various flow rates. BGI and UK HSL have laboratory and field verified the model for the Sharp Cut Cyclone and by doing so have designed a new generation of cyclones with collection and separation parameters equal to inertial impactors (BGI website, 2011)

Data is conclusive (Kenny, 1997) that the Stairmand cyclone design cut point is not sharp since the inlet vortex and outlet tube diameters are fixed geometry, and therefore this design is rapidly becoming obsolete, being replaced with the Sharp Cut Cyclone design.

No cyclone design can have an infinitely sharp cut-off, with all particles below 1 µm, for example, being let through and all particles above that size rejected. Inlets are designed so that 50% of particles of the critical size are rejected, but the curve of percentage rejected versus particle size varies between designs. Cyclones generally have a less sharp cut-off curve than inertial impactors, and the reference design is, therefore, usually an impactor. Impactors have not been considered by SAE E31 due to their use of oil/grease on the impaction surface which would contaminate the sample at elevated (above ambient) temperatures.

However, the SCC design has been accepted by both the US EPA and EU as a replacement for impactors employed to obtain ambient air reference PM measurements due to the steep penetration curve characteristic, whereas the flatter penetration curve attribute of the Stairmand (and other types) design does not meet the tight constraint required for reference size-selective measurements.

In order to minimise measurement uncertainty and follow reference size-selective criteria the BGI PM1 SCC was utilised in this study rather than the commercially available URG (Stairmand) type. A schematic of the cyclone is shown in Figure 48 with the measured penetration efficiency curve given in Figure 49 (Gussman, 2000).

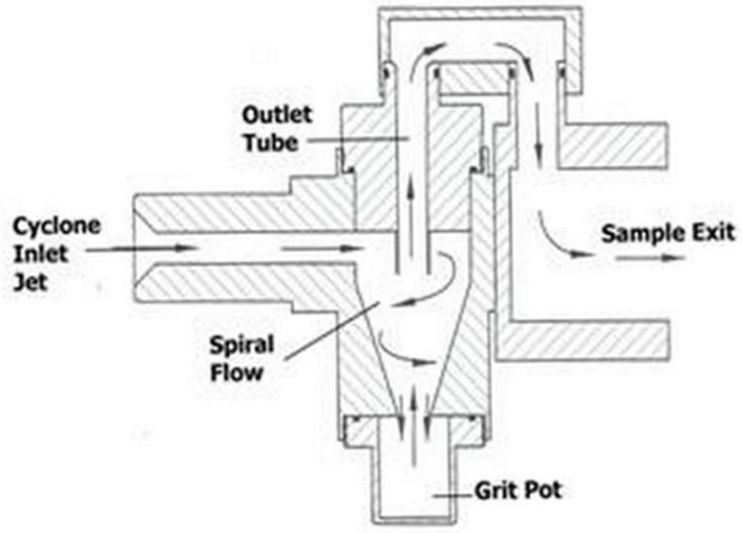


**Figure 48 Schematic of a BGI Sharp Cut Cyclone (SCC)**

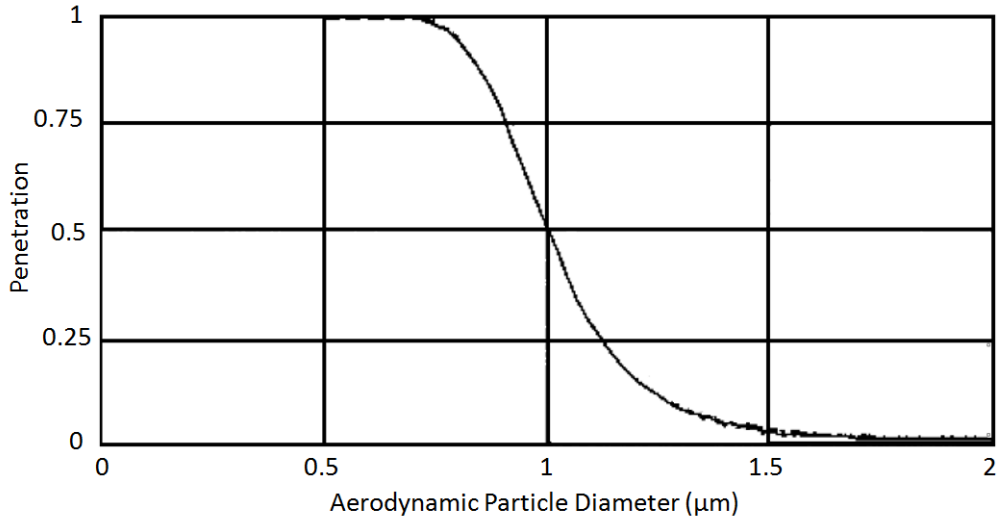


**Figure 49 BGI PM1 SCC measured penetration curve (at 16.7 SLPM)**

An analysis of the cyclone performance has not been carried out in this study but it is noted that current non-definition of cyclone performance specifications in the SAE E31 Committee proposed sampling system is an existing gap in the measurement uncertainty as outlined in section 9.4.

Also as the existing SAE E31 intentions are to utilise commercial products wherever possible in ARPs, this has necessitated the need to operate commercial cyclones at flow-rates significantly higher than their design point. This has the result of moving the penetration curve to smaller particle sizes. For the non-volatile PM mass measurement this has the undesired effect of significantly increasing the measurement uncertainty if the largest combustion generated PM are curtailed. OPC (Optical Particle Counter) data obtained during SAMPLE II on a modern full-size gas turbine exhaust indicated that there were a few (single count) particles at 0.4µm. Even though few in number, these 'large' particles equate to a significant fraction of the measured non-volatile mass concentration. As long as the cyclone penetration curve does not overlap <0.45µm (operating at 25±5 SLPM) then there will be no impact on the non-volatile mass measurement. The SCC cyclone type is less likely to be impacted by this effect than the Stairmand type due to sharpness of the penetration curve.

The performance specifications for the cyclone should not only emphasise the $d_{50}$ cut-point (which should be 1µm with error range still to be defined) but in addition the 'Sharpness' specification. The Sharpness parameter is defined by Equation (8):

$$(D_{16}/D_{84})^{0.5} \quad \textbf{(8)}$$

The cyclone Sharpness performance specification could follow the existing EU PM1 SCC specification (≤1.17).

In addition, due to the comparable build cost of custom versus commercially available cyclones it would be possible to specify the exact requirements of a $d_{50}$ and Sharpness at the

standardised flow rate of 25 SLPM and build custom ARP cyclones to meet this operating requirement. This option should certainly be explored in further cyclone studies.

A cyclone performance study is required to define the required specifications which will then address the measurement uncertainty issues.

## 5.3 Built Transfer system component description list

A cutting list detailing all of the parts used in the build of the transfer section of the consortium sampling system is given below in Table 19 and a photograph of the built sampling system in use testing behind a full scale engine is given in Figure 50

**Table 19 Component description list**

| Section | Component | Part |
|---|---|---|
| ALL | Fittings | Stainless steel, unions smooth bore, no shoulders present. |
| 3PTS | Splitter 1 | Bespoke construction<br>Trace heated to 160°C<br>Material: Stainless Steel<br>Angle of branch split: 30°<br>Two 2-branch splitters were utilised in series. The upstream splitter was the pressure relief.<br>All Splitter1 branches ID 7.74mm |
| | Pressure relief branch | ID 7.74mm<br>Manual ball-valve , full-bore 7.74mm |
| | Dilutor1 (PM branch) | 160°C Trace heated Dekati DI-1000, with heated diluents (provided by R-R Derby) |
| | Gaseous and Smoke branch | Electrically heated to 160 +/-15°C, grounded Carbon-loaded PTFE, ID 7.74mm, length 25m (provided by R-R Derby) |
| 4PTS | PM Transfer line | Electrically heated to 160 +/-15°C, grounded Carbon-loaded PTFE, ID 7.74mm, length 25m |
| 4PTSc | Cyclone | Heated to 160°C<br>BGIUSA SCC2.229<br>Sharp cut cyclone 1 micron at 16 SLPM (Provided on loan by NRC) |
| | Splitter 2 | Bespoke construction<br>Trace heated to 160°C<br>Material: Stainless Steel<br>Angle of branch split: 30°<br>Two 2-branch splitters were utilised in series. The upstream splitter was the number measurement.<br>All Splitter2 branches ID 7.74mm |
| | Mass flow controller and pump | Micromotion coriolis cmf010 , linear air pump (both provided by Cardiff Uni) |
| | $CO_2$ analyser | Signal MGA NDIR gas analyser (provided by Cardiff Uni) |
| 4PTSm | Mass transfer line | Heated to 160°C, Stainless Steel, ID 7.74mm, length 1.5m |
| 4PTSn | Number transfer line | Heated to 160°C, Stainless Steel, ID 7.74mm, length 1.5m |
| | Volatile removal device | Bespoke VPR constructed to PMP specifications, see Task 1 for detailed description |
| | $CO_2$ analyser | Bespoke DLR atmospheric analyser, range 0 to 1000ppm |

It should be noted that Dekati diluter used in the building of the system is the same component lent to SAE E31 for concept sampling system testing under the FAA sponsored AAFEXII measurement campaign (March 2011).

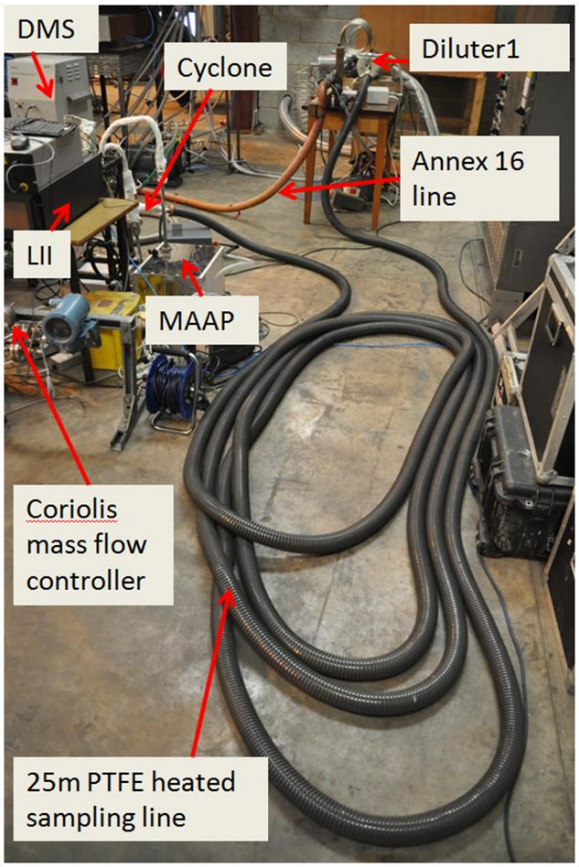


**Figure 50 Photograph of consortium built sampling line set up during full size APU engine test**

## 5.4 Conclusions of Task 2

1. A sampling system meeting current specifications laid out by the SAE E31 Committee has been designed and built and performed suitably for use in testing a full scale APU engine.
2. Performance specifications for specific components of future standardised sampling systems have been proposed by the consortium but have not been currently ratified by the SAE E31 Committee at present.
3. Further work will be required to define a specification suitable for volatile particle removal efficiency for use in aero type exhausts as it is felt the current PMP approach may not provide low enough uncertainties.
4. A cyclone performance study is required to define the required specifications which will then address the measurement uncertainty issues

# 6. Task 3a: Full-Scale Non-Certification Engine Testing Using Sheffield University Rolls-Royce Artouste Auxiliary Power Unit Gas Turbine Engine.

## 6.1 Introduction

In order to further demonstrate the functionality of the sample train design discussed in Section 5, it was necessary to conduct a measurement campaign behind a full-scale gas turbine engine. In order to ensure availability, which is not always guaranteed on modern full scale aero gas turbine engines, test campaigns were performed at the University of Sheffield's Low Carbon Combustion Centre to demonstrate the non-volatile particulate sampling system on a small, low power, low thrust gas turbine exhaust. These, intermediate scale, APU combustion tests fit in the range of possible combustion analysis between laboratory bench scale testing and large full engine tests, the APU test requires orders of magnitude less fuel to run than a large scale modern engine which also gives significant advantage in terms of reduced consumable testing costs and thus increases the potential test time available.

As this scale of testing was conducive to numerous days of testing it facilitated a suitable vehicle to conduct a detailed quantification study investigating line losses along the proposed non- volatile PM measurement sampling line. As such the APU was run at different power conditions and detailed size and number measurements were made at different locations along the SAE E31 Committee proposed sampling line using a DMS & SMPS.

## 6.2 Description of Sheffield University Rolls-Royce Artouste Auxiliary Power Unit Gas Turbine Engine test.

### 6.2.1 Description of APU test bed

The test bed gas turbine engine is a re-commissioned Artouste Mk113 Auxiliary Power Unit (APU), which has a two stage turbine connected to a centrifugal compressor through a single shaft. The engine test bed facility also provided an ideal experimental platform to evaluate the performance of the sampling system in terms of particle line loss calculations, as despite the apparent age of the engine, the simplicity of the hardware allowed for easy close-by instrumentation and simple start/stop if there were experimental sampling issues.

The Artouste combustor is an annular, radial flow combustor with a fuel flinger injector as shown as shown schematically in Figure 51. This APU found application in the RAF Victor Bomber (retired 1993), supplying both air for engine starting and electrical power to the aircraft systems.

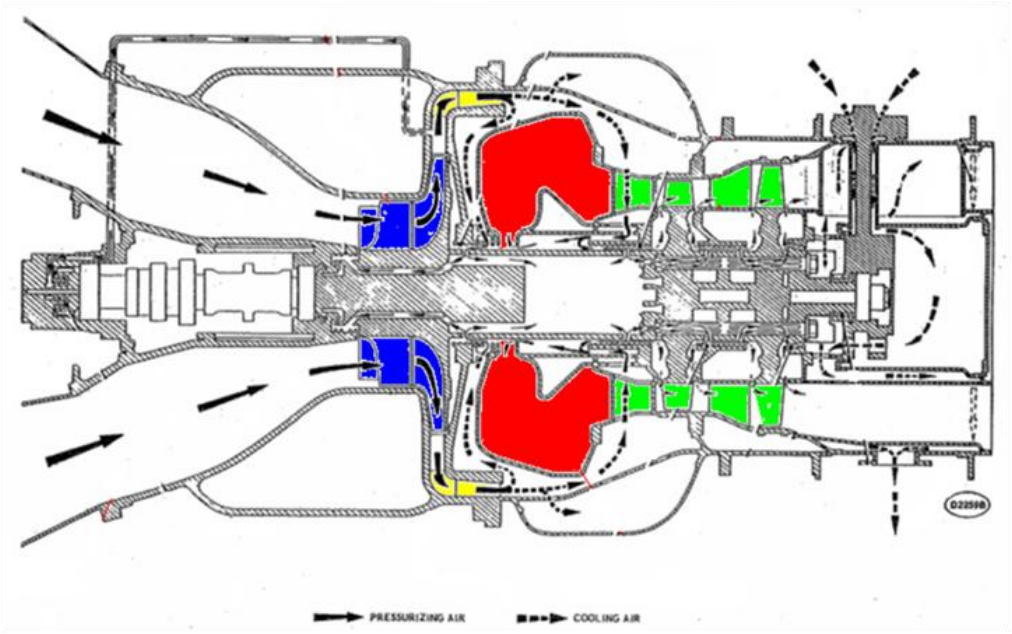


**Figure 51 Schematic representation of Rolls-Royce Artouste APU engine used for demonstration of proposed non-volatile PM sample line**

### 6.2.2 Description of Sampling System and Instruments used

A stainless steel mount was fixed behind the APU exhaust so that the installed sampling probes would sit no further back than half an exhaust diameter behind the engine exhaust plane as required per the Aerospace Recommended Practice (ARP1256). Exhaust blockage was no more than 5% of the exhaust exit plane. Two stainless steel, single point 3/8 inch (7.74mm ID) emissions probes were mounted with one being used to provide a 'policeman' check of the particulate signature over the entire test period (similar to HES setup) and the other being used to supply sample to the sampling system. The probes can be seen on Figure 52. A thermocouple was located outside the exhaust flow on the sampling line to check that the sample temperature did not drop below 160°C before entering heated line section.

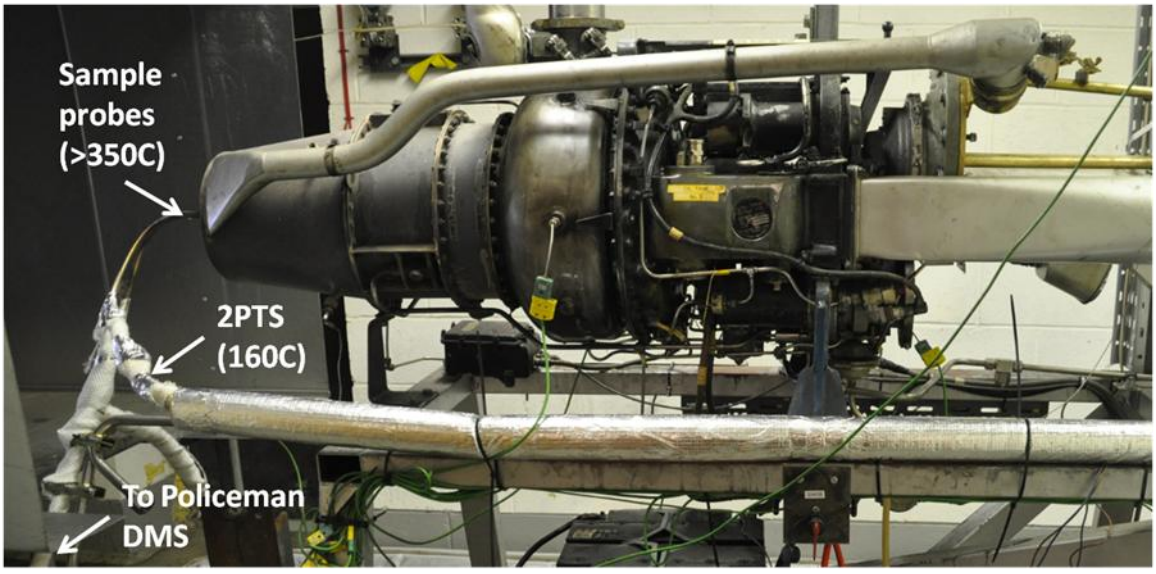


**Figure 52 Photograph of Sheffield University's Full scale Rolls-Royce Artouse APU engine fitted with sample probes used for this study**

A schematic of the bespoke sampling system built and coupled to the proposed non-volatile PM measurement sampling train and measurement suites are given in Figure 53 and Figure 54. The points at which experiments to determine line penetration are given as positions 1, 2, 3, 4 & 5 which correspond to:

1. upstream of primary diluter (at start of proposed non-volatile PM sampling line)
2. downstream of primary diluter (Dekati DI1000)
3. after the 25m trace heated carbon loaded PTFE sample line
4. after 1µm sharp cut point cyclone prior to mass measurement point
5. after proposed PMP approved VPR

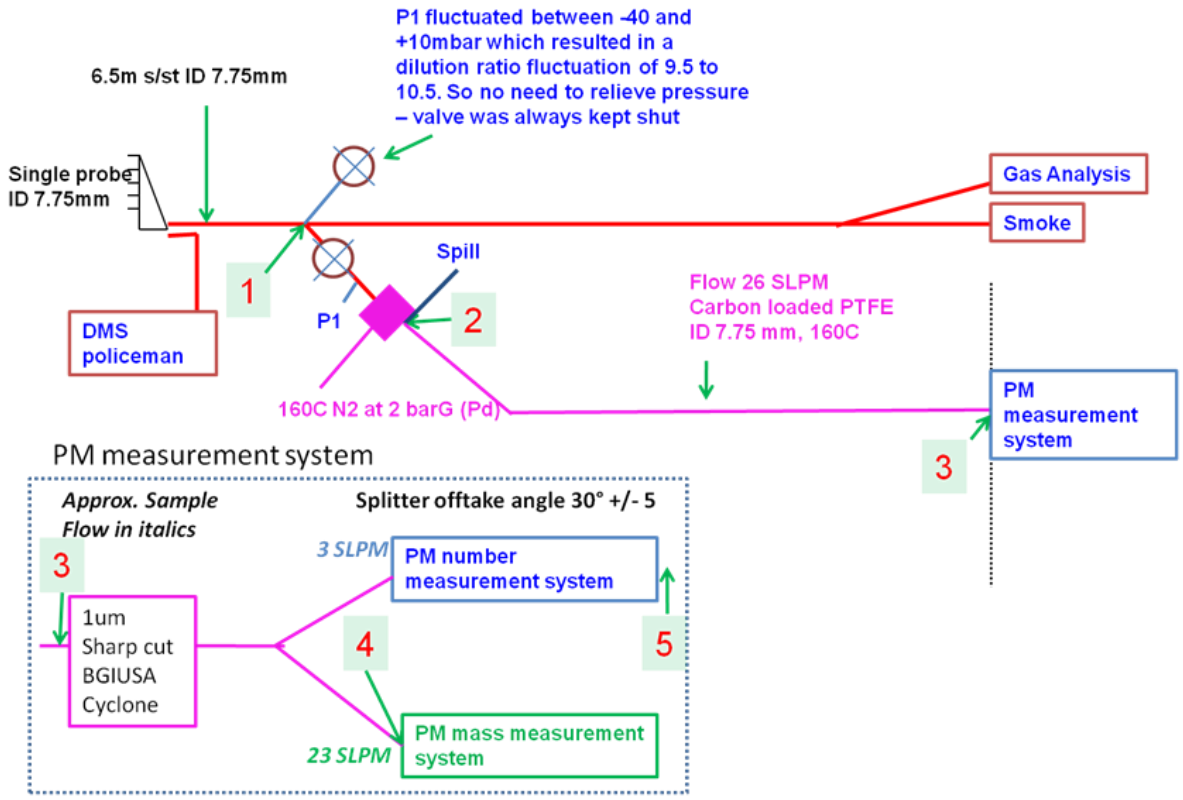


**Figure 53 Schematic of sampling set up utilised during APU trials at Sheffield University**

It can be seen in Figure 53 that the sample lines consist of a sampling probe section and standard Annex 16 gaseous and smoke line (red line) off which the proposed SAE E31 Committee non-volatile PM sampling line (pink line) connects via a full bore high temperature ball valve and at the end of the sampling line the number and mass measurement suites are attached (blue enclosure) which are showed in greater detail in Figure 54.

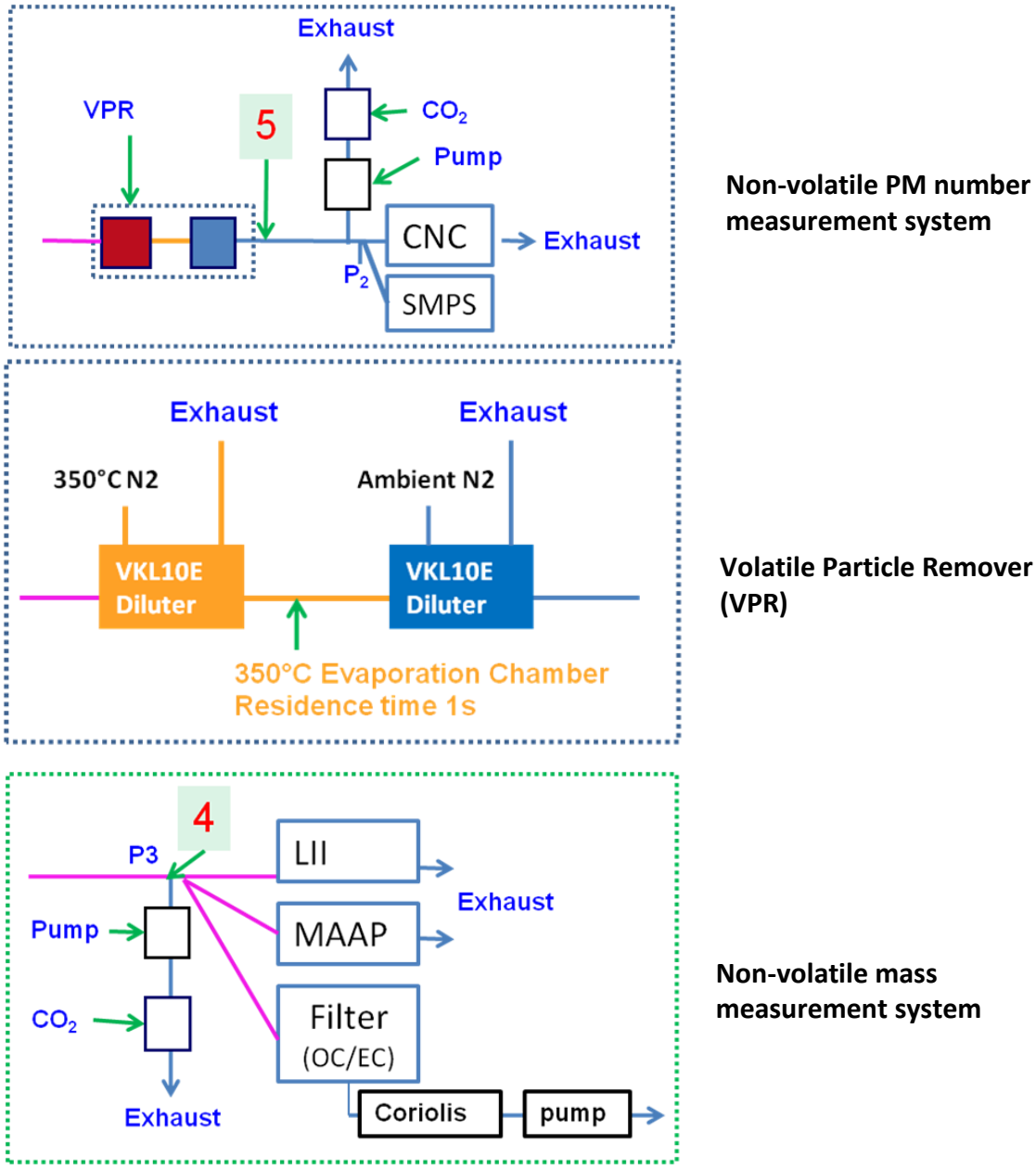


**Figure 54 Proposed ARP measurement systems**

As discussed earlier an Annex 16 gaseous and smoke line was fitted to the APU and conditioned exhaust sample was drawn into the Sheffield University Mobile Emissions Laboratory through a 1/4 inch heated line before being split between the gaseous analysis suite and smoke meter using a y-connector. The sample lines were maintained at 160±15°C per ARP1256C, with a minimum bend radius of 10x the line diameter. A constant sampling flow rate (and system pressure) was maintained to the gaseous analysis equipment by using a metal bellows pump, with excess sample being exhausted through a back pressure regulator. Gaseous emissions (Unburned Hydrocarbon 'UHC', Carbon Monoxide 'CO' and Nitrous Oxides '$NO_x$') were measured per ARP1256c. UHC was monitored using a flame ionization detector (Signal 3000-M hydrocarbon analyser), with CO and $CO_2$ measured using a non-dispersive infrared analyser (Rosemount Binos 1000).

An Eco Physics CLA EL ht (chemiluminescence) analyser was used to record NOx in this experiment. The chemiluminescence reaction, namely the light emitted from the transition of electrically excited $NO_2$ (excited by the reaction $NO + O_3 \rightarrow NO_2$), back to its ground state, is the principle employed to measure NO. The NOx concentration is established by first passing the exhaust gas through a catalysed thermal reaction ($2NO_2 \rightarrow 2NO + O_2$).

The analysers were zeroed, and then spanned using appropriate gas concentrations just prior to the beginning of each experiment, with the zero and span drift established at engine shutdown. Instrument linearity and interference effects were assessed and corrected for as per the aerospace recommended practices (ARP1256 rev. D, and ARP1533 rev. A) the experimental error associated with the measurement of emissions is estimated to be approximately ±2% of reading.

SAE smoke number was established using a Richard Oliver smoke meter, Whatman No. 4 filter paper and a reflectometer (BOSCH ETD 02050) per ARP1179D. The technique involves passing a set volume of sample through the conditioned filter paper, and measuring the change in the absolute reflectance of the filter paper due to the PM collected.

As discussed the main objective of the experiment was to quantify penetration losses through the proposed SAE E31 Committee non-volatile PM sampling line as such there is the need to sample at various positions as discussed earlier as such an experimental plan was required detailing for each specific experiment where the analyser would be. This was an important task as all flows in the line had to be balanced in order to show comparative readings at each of the 5 positions, as a major outcome of the SAMPLE II project was that sample line losses were largely influenced by residence time and hence flow rate. As such the sample line had some strategically positioned pumps which could be switched on and off depending on experiment to ensure matched flows. A schematic of the experimental plan is presented in Figure 55 with associated flow rates in each section for the 10 different experimental points studied to quantify line penetration.

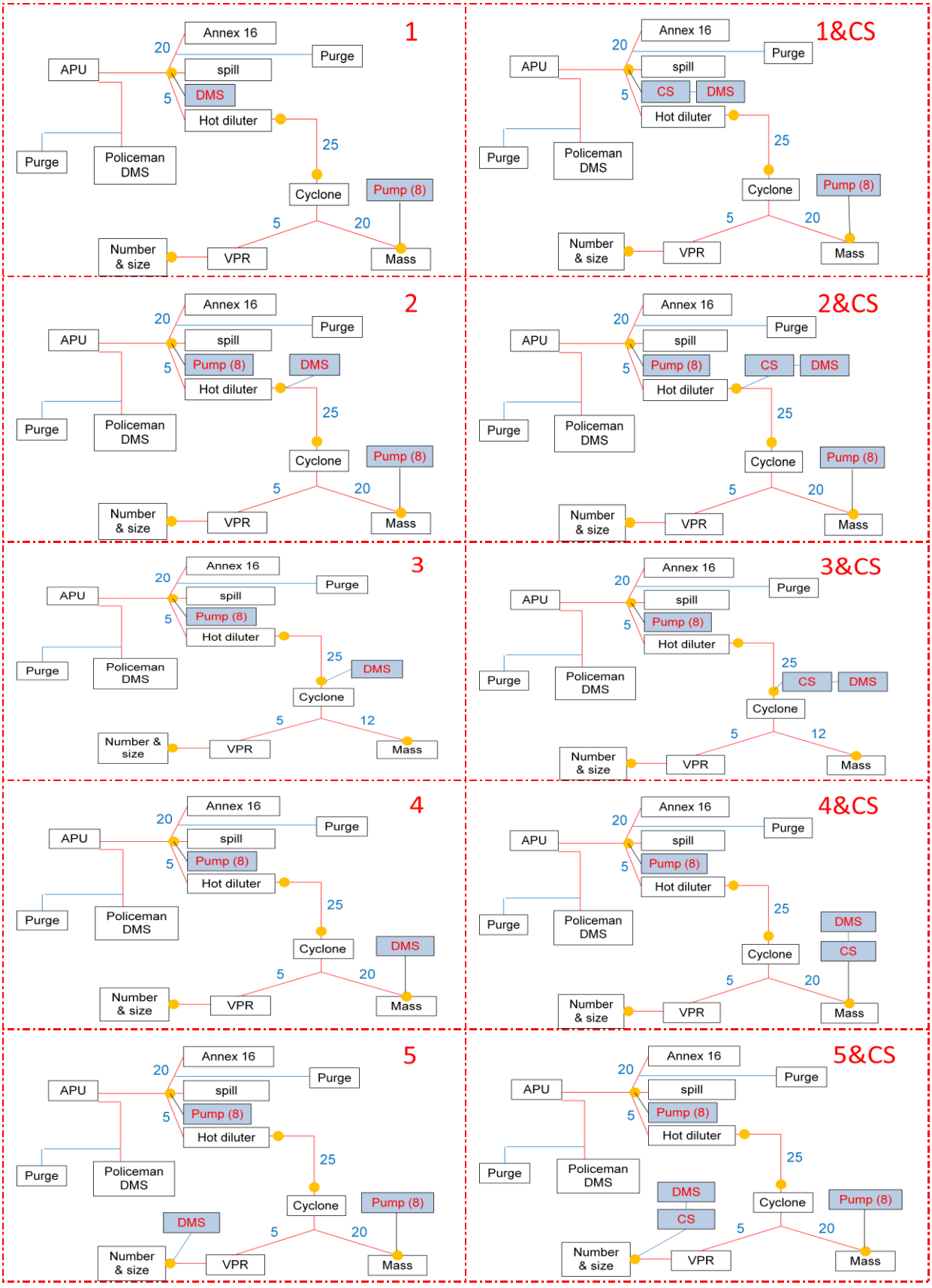


**Figure 55 Experimental plan schematics for line penetration study showing matched flowrates**

As can be seen from the experimental plan and as discussed earlier 5 separate locations were interigated using the DMS and the DMS in series with the University of Minessota bespoke high flow CS. As the CS was shown to remove nearly 100% of volatile fraction during the PMP study (Figure 27) it was thought by conducting the experiment in this fashion it would allow for the study of total exhaust PM losses, along with the non-volatile PM losses, along the consortium built non-volatile PM sample line (which meets the currently proposed SAE E31 Committee sampling line) which could then be compared with theoretical physical models.

Photographs of the consortium built PM sampling line and instrument suite as set up during the full scale APU engine test is shown earlier in Figure 50 and below in Figure 56 respectively.

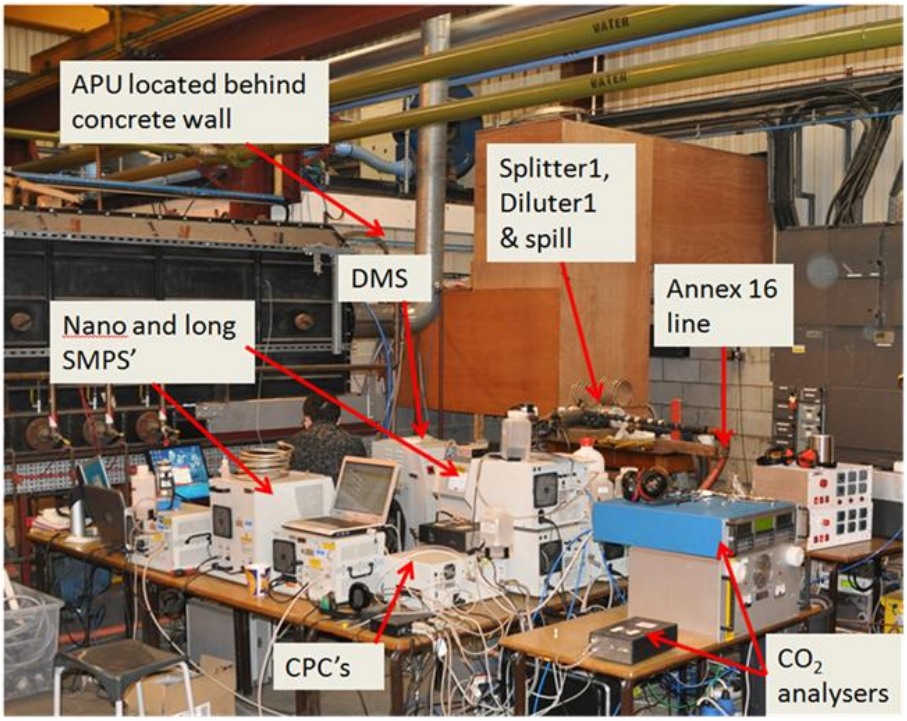


**Figure 56 Photograph of instrumentation suite used during full scale engine APU testing**

### 6.2.3 APU Test Conditions

At the start of a test run, the APU was allowed to stabilise for five minutes and each sampling condition was conducted typically within a ten minute experimental window. Logging of key engine and thermodynamic properties occurred during all test runs. The time taken and steadiness of the operating conditions for the APU to stabilise for each of the two power conditions can be seen in Figure 57 & Figure 58. The test campaign involved multiple idle and full power test runs.

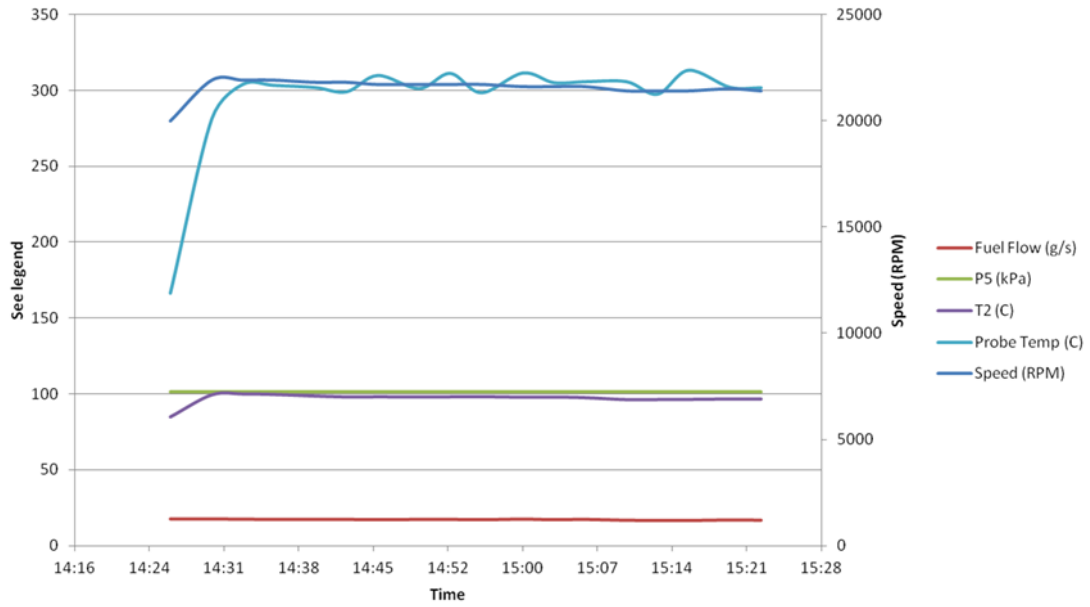


**Figure 57 APU engine data example at idle condition**

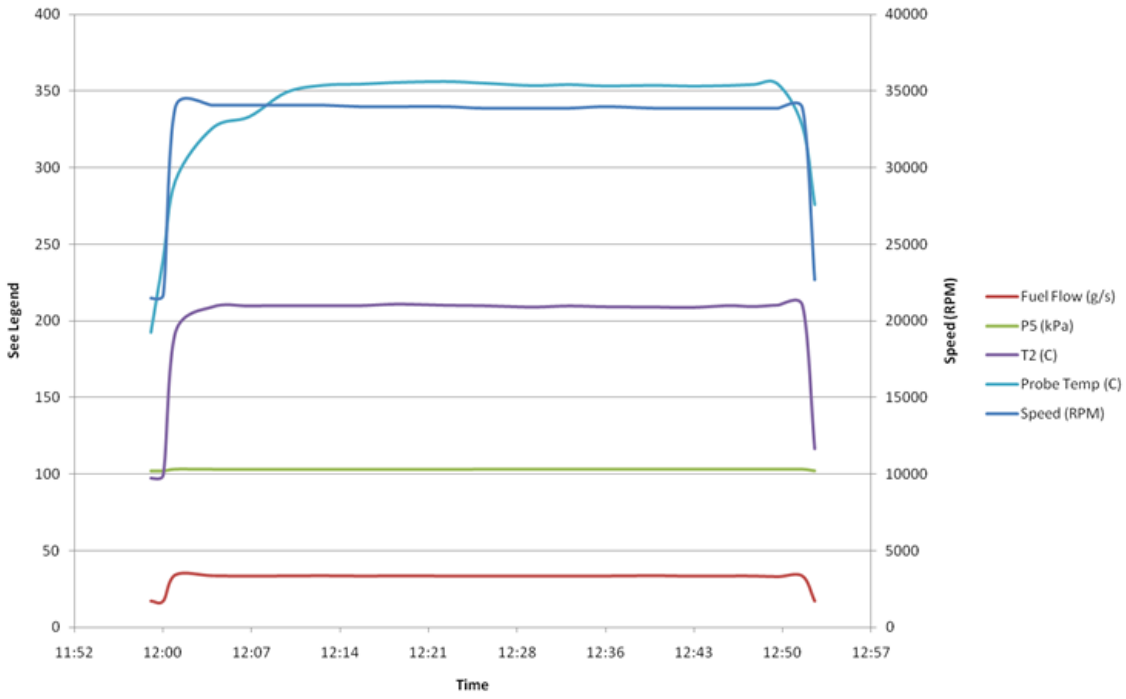


**Figure 58 APU engine data example at full power condition**

Typical Emissions Index (EI) (g/kg) values for gaseous emissions data for both power conditions are shown below in Table 20:

**Table 20 Typical EI gaseous emissions for APU operating conditions**

| | AFR | EI $CO_2$ | EI CO | EI NOx | EI UHC |
|---|---|---|---|---|---|
| **Idle** | 68.1 | 3061 | 71.3 | 1.8 | 9.2 |
| **Full Power** | 63.5 | 3155 | 25.8 | 4.1 | 1.1 |

The typical raw gaseous emissions data for both power conditions is also given as corrected dry volumetric concentration below in Table 21

**Table 21 Typical corrected volumetric dry gaseous emissions for APU operating conditions**

| | AFR | $CO_2$ | | CO | | NOx | | UHC | |
|---|---|---|---|---|---|---|---|---|---|
| | | % | σ | ppm | σ | ppm | σ | ppm | σ |
| **Idle** | 68.1 | 2.9 | 0.3 | 1100 | 34 | 19.0 | 0.17 | 273.2 | 11.2 |
| **Full power** | 63.5 | 3.20 | 0.04 | 409.0 | 9.3 | 37.6 | 1.03 | 34.5 | 1.4 |

Typical values for smoke and particle emissions data for both APU power conditions are also given for smoke number, LII mass and non-volatile PMP number concentrations are shown below in Table 22.

**Table 22 Typical smoke conditions for APU operating conditions**

| | Smoke | | Non-volatile particle mass (LII) | | Non-volatile number (PMP VPR + 7nm CPC) | |
|---|---|---|---|---|---|---|
| | SAE | σ | $mg/m^3$ | σ | $\#/cm^3$ | σ |
| **Idle** | 7.5 | 1.1 | 0.297 | 0.011 | 5.2E+07 | 1.7E+05 |
| **Full Power** | 19.2 | 0.9 | 0.764 | 0.014 | 7.8E+07 | 2.4E+05 |

An hour long plot of the DMS taken at Sampling Point 1 (before the primary diluter) is given in Figure 59 showing the uniformity of the PM size signature over an hour long test run.

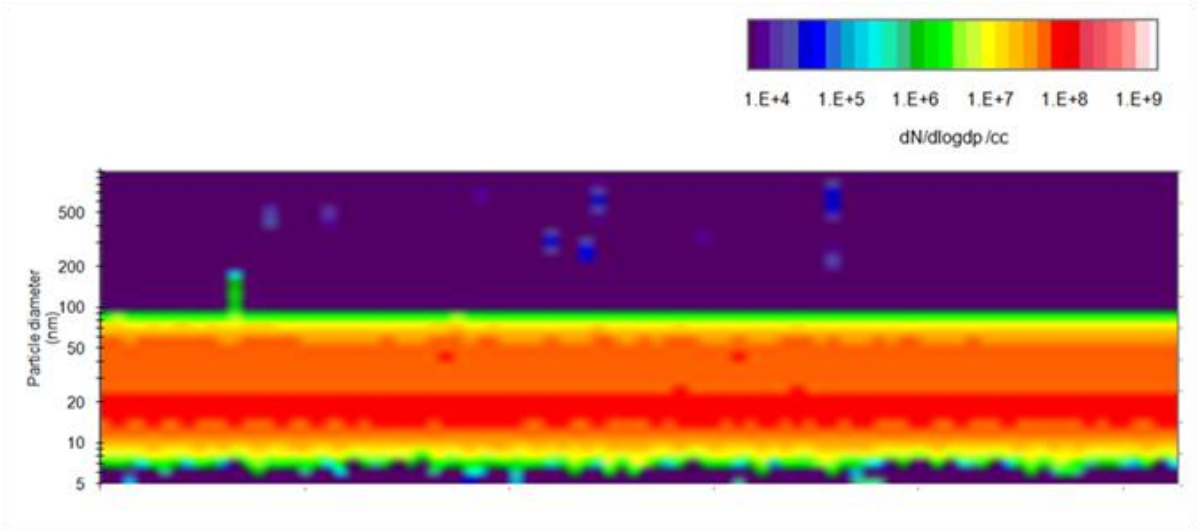


**Figure 59 Hour long DMS plot showing steady nature of PM size distribution behind full scale APU engine operating at an idle condition**

As can be seen from the above Figures and Tables by the low variance and standard deviations witnessed for the APU running conditions make this unit a suitable vehicle for conducting repeated experiments making it ideally suitable for use in line loss penetration studies.

## 6.3 Results and Discussions of Full Scale APU Engine study

As discussed earlier the two main objectives of the full scale APU engine experimental programme was to appraise both the operability and functionality of the consortium built (proposed SAE E31 Committee) non-volatile PM sampling line along with the quantitative measurement of PM losses along its length.

### 6.3.1 Operability and Functionality of Consortium Built Non-volatile PM Sampling Line on Full Scale APU Engine

As expected the consortium built PM sampling line designed and discussed in Section 5, and broadly similar to that trialled during the full scale engine testing in SAMPLE II and AAFEX II was again demonstrated and performed well within expectations on a small scale, low power, low thrust APU which highlights the system's ability to cope with low inlet pressures at the splitter ranging from -38mbar at idle to -2mbar at full power meaning that the pressure relief system was not needed during this trial. It was observed that the dilution ratios witnessed for the primary (Dekati DI 1000) diluter did not significantly vary over the two power ranges giving a dilution ratio range of 10.5 at idle condition compared with 9.7 at full power.

The consortium built non-volatile PM sampling line was trialled with two types of VPR namely the consortium bespoke eductor based VPR and the AVL APC400 rotary diluter based VPR and performed well under both configurations.

### 6.3.2 Line Penetration Study of consortium built Non-volatile PM Sampling Line on Full Scale APU Engine

As discussed earlier the penetration losses along the consortium built non-volatile PM sampling line were examined using a DMS and SMPS with and without a University of Minnesota bespoke catalytic stripper.

#### *6.3.2.1 Penetration through primary diluter*

The penetration across the primary diluter was examined using a DMS and the size distributions from sample point 1 and sample point 2 are presented below in Figure 60.

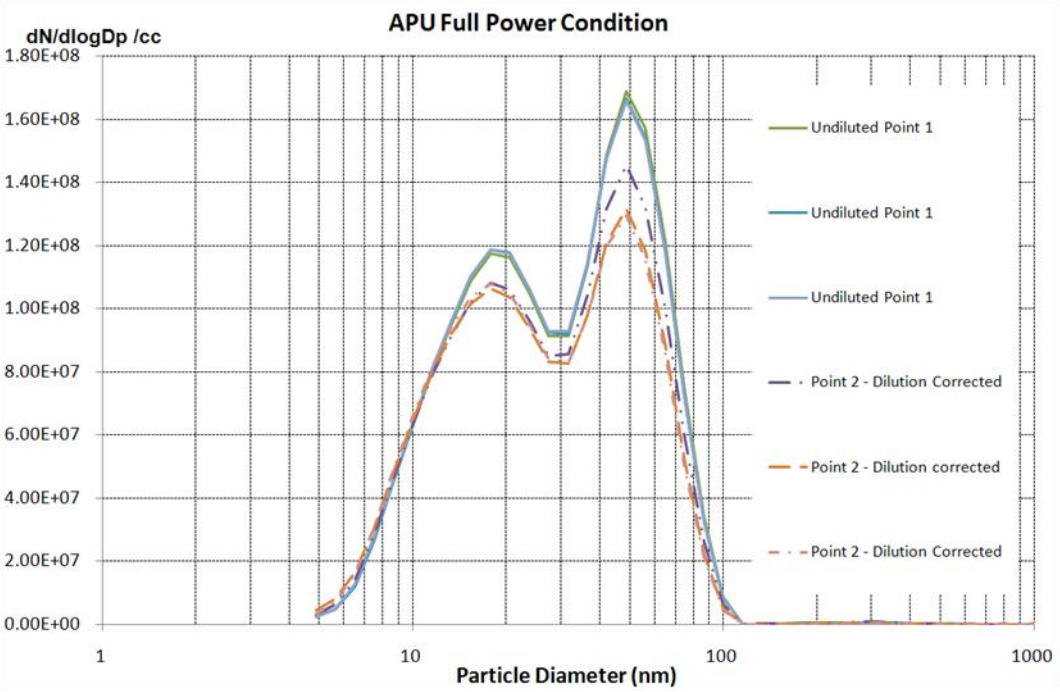


**Figure 60 DMS size distributions upstream and downstream of primary Dekati DI1000 eductor diluter**

As can be seen three repeats were repeated over numerous test runs showing good repeatability of data from the APU. Also as expected there was a small loss of particles witnessed in the diluter which could be accounted for in future ARP methodology by including a PMP type PCRF.

#### *6.3.2.2 Penetration through sampling lines*

Figure 61 and Figure 62 shows the DMS size distributions measured with and without a CS at the different sampling points along the consortium built non-volatile PM sampling line measuring behind a full scale APU engine operating on idle power. As can be seen as expected there are noticeable losses along the sampling system for PM across the entire size distribution with higher losses witnessed for the lower sized PM as would be consistent with diffusion loss models.

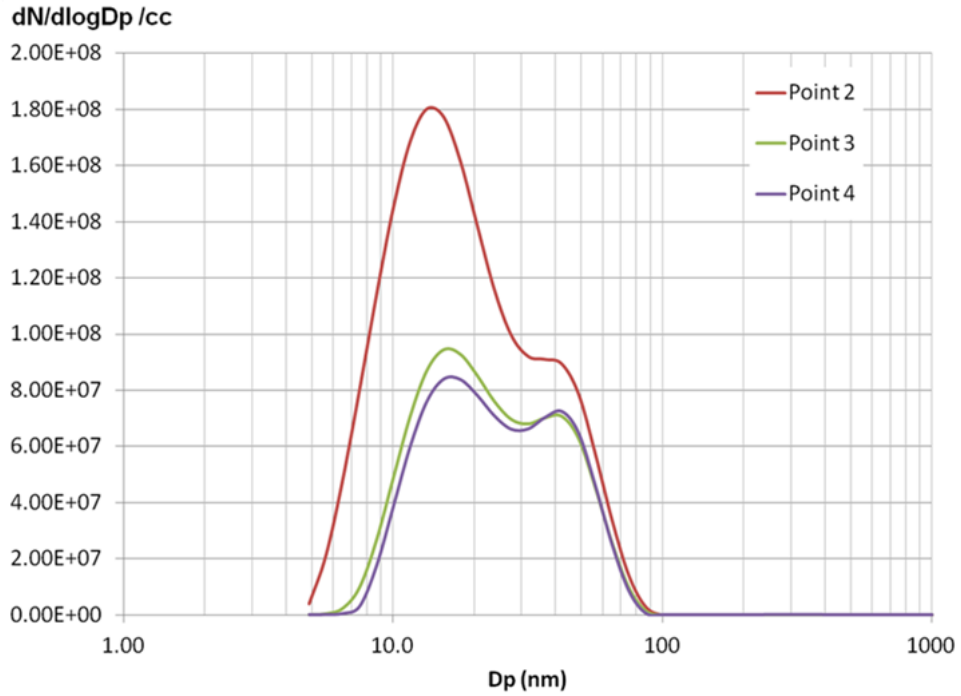


**Figure 61 DMS size distributions measured at the different sampling points along the consortium built non-volatile PM sampling line behind APU on idle power**

It can be seen when comparing Figure 61 to Figure 62 that the CS is removing a large number of volatile PM as witnessed by the noticeable shrinkage in number concentration of the primary nucleation mode peak.

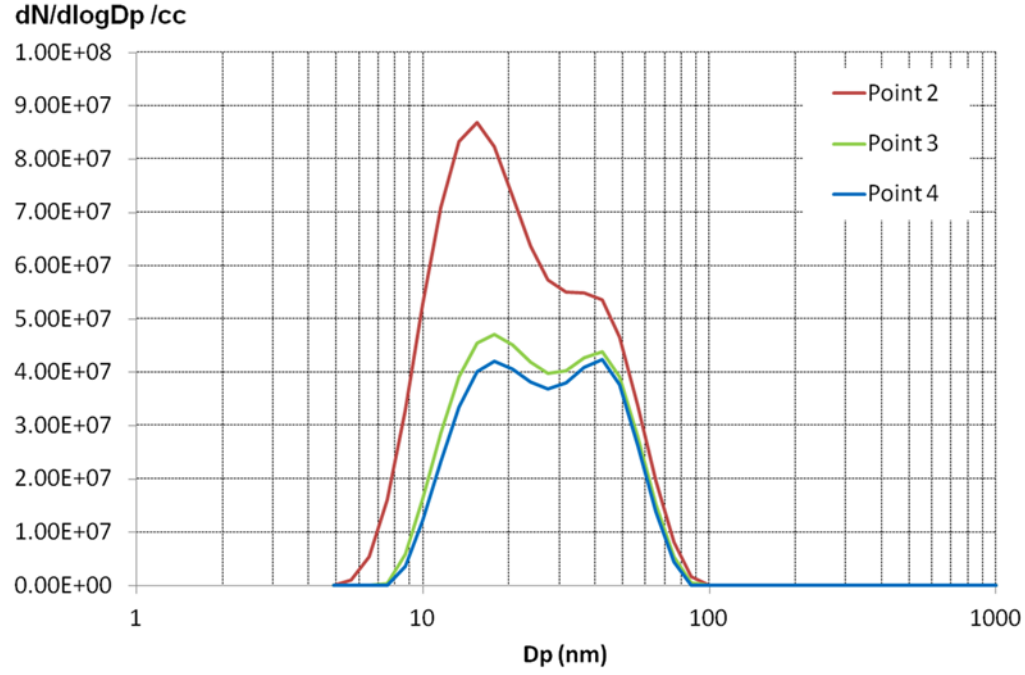


**Figure 62 DMS size distributions measured behind a CS at the different sampling points along the consortium built non-volatile PM sampling line behind APU on idle power**

Similar trends are witnessed when inspecting the data derived utilising the SMPS with and without a CS as presented by Figure 63 & Figure 64. Once again as was witnessed during earlier trials there appears to be discrepancies in the size distributions witnessed with SMPS compared to DMS methodologies, with the SMPS tending to show mono-modal distributions.

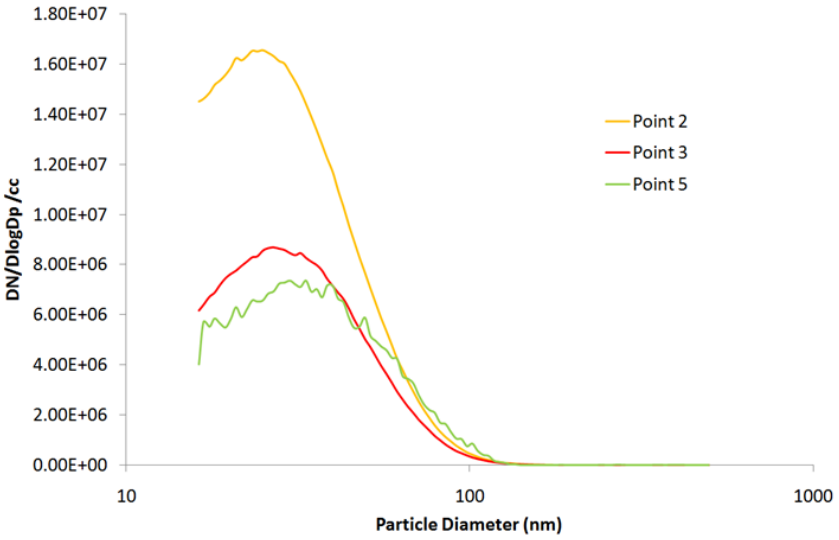


**Figure 63 SMPS size distributions measured at the different sampling points along the consortium built non-volatile PM sampling line behind APU on idle power**

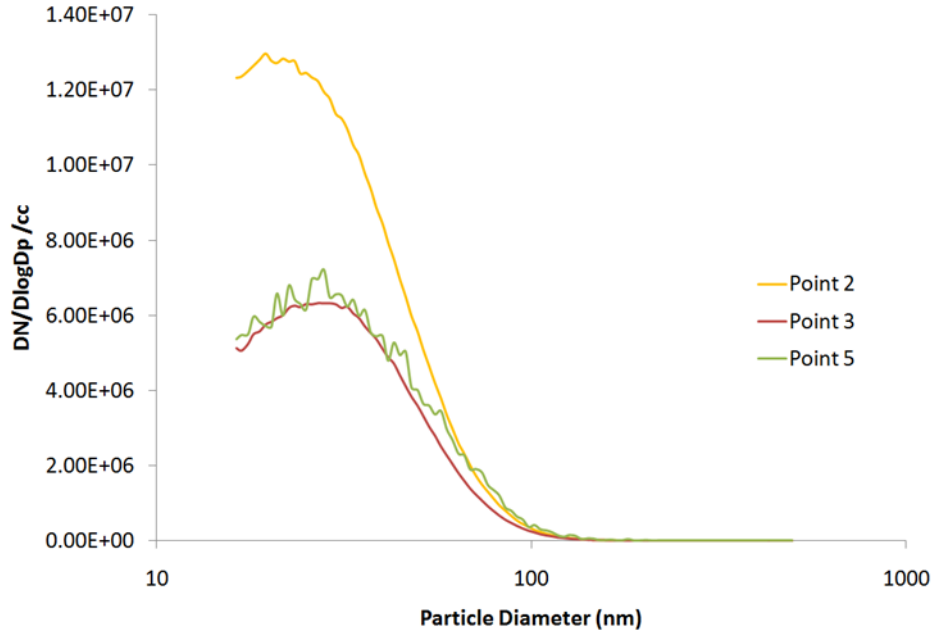


**Figure 64 SMPS size distributions measured behind a CS at the different sampling points along the consortium built non-volatile PM sampling line behind APU on idle power**

It is seen from all of the above Figure 61 - Figure 64 that the majority of the PM losses in the sampling line occur between sampling point 2 and sampling point 3 when compared with losses between sampling point 3 and 4. This trend fits with the conclusions stated in

SAMPLE II that higher losses were witnessed for increased residence times /line length and higher losses were observed in carbon loaded PTFE lines compared with comparable stainless steel lines, thus higher losses in a 25m PTFE line would be expected compared with a shorter (2-3m) stainless steel section and cyclone.

The associated losses measured by DMS along the 25m line (between sampling point 2 and 3) were compared with the predicted losses modelled using diffusion loss theory and are presented in Figure 65.

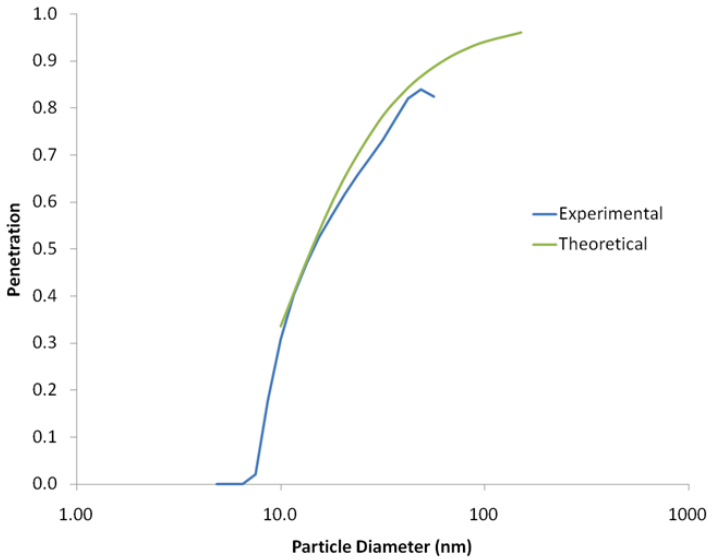


**Figure 65 Comparative DMS experimental and modelling predictions for penetration along a 160°C 25m sampling line**

As can be seen the measured and modelled data show excellent agreement, however, it is noted that this sample is already aged and diluted so should show little extra thermophoretic loss. This is in contradiction to previous studies conducted on the HES (Sevcenco et al. 2010) which showed poor agreement between models and experimental, however in this case the upstream measurement was taken on raw exhaust.

A similar modelling approach was conducted with the data collected with the SMPS in series with a catalytic stripper the results of which are given in Figure 66.

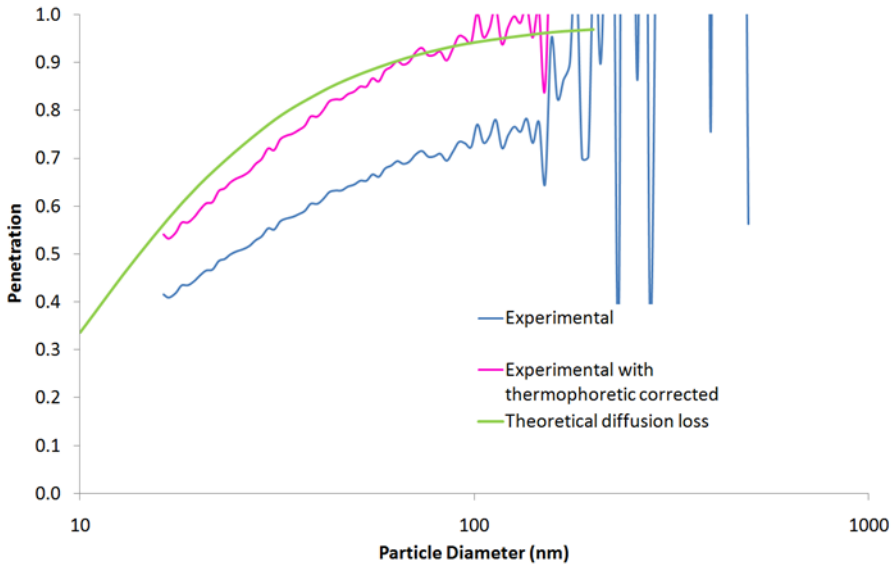


**Figure 66 Comparative SMPS & CS experimental and modelling predictions for penetration along a 160°C 25m sampling line**

It is witnessed in this case that if only diffusion losses are accounted for in the 25m line and CS then there is a poor agreement between model and experiment (blue curve), however, when thermophoretic losses witnessed in the heated CS (350°C) are also added to the model (pink line) then good agreement is shown.

The ratio of total to non-volatile PM can also be examined at each sampling point by plotting the DMS data taken with and without a CS and correcting for expected losses within the CS. The data is presented for four sampling points in Figure 67.

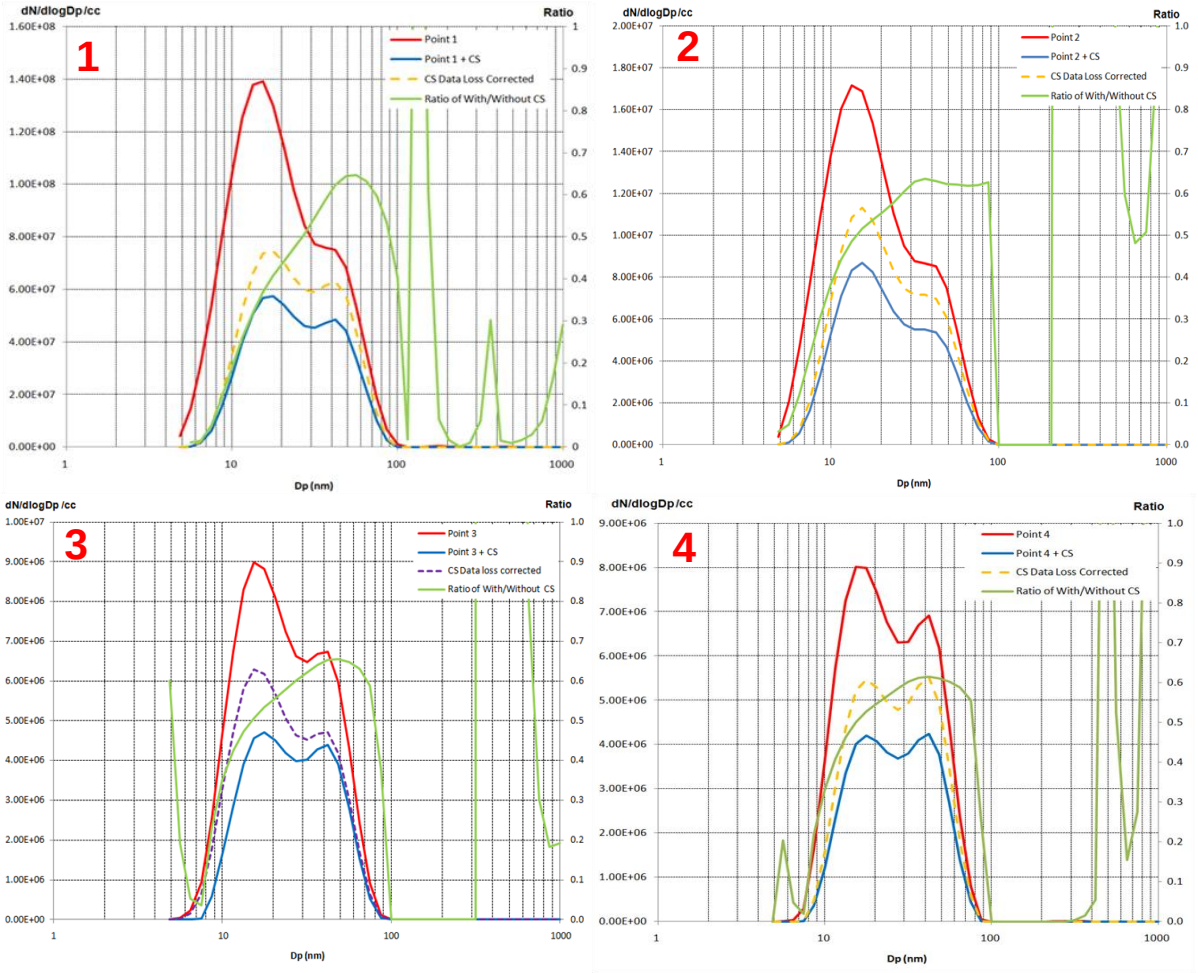


**Figure 67 DMS Size distribution for different sampling positions with and without CS**

As can be seen at each point as expected there are lower number concentrations for the DMS measuring behind a CS (blue line) compared to DMS measuring total PM, some of this reduction will be accounted for in thermophoretic and diffusion losses associated with the CS as such these losses are accounted for and are shown (dashed lines). It is again noticed that the reductions happen across the entire size distribution. It is noticed that at sample point 1 there are most reduction at the small nucleation mode size range which would be the expected size of volatile PM.

The ratio of assumed volatile to non-volatile PM is shown on each plot (green line) and it can be seen that typically the ratio of volatile PM is 50% of the total PM across the entire size distribution. This is an unexpected finding as contemporary knowledge within the SAE E31 would suggest that pure volatile particles are typically smaller than 20nm and any volatile particles bigger than this are volatile coated particles. However, if this is a correct assumption then this experiment suggests that there are large numbers of small solid particles, as if large particles were coated in a thin layer of volatile then on the removal of the volatile coating in terms of number there would not be a large reduction in particle concentration of large particles but a shift in the particle size in the accumulation mode peak towards a smaller size. As there does not seem to be an obvious shift in size of the accumulation mode then this supports that coated particles must be small, thus they are appearing in the nucleation mode of the non-volatile particle trace.

Figure 68 shows SMPS particle size distributions using two models of TSI SMPS (nano & long DMA configured) in order to obtain the complete exhaust size distribution from 5 to 400nm. The SMPS' sampled from each designated sampling point with a CS along the sampling system to assess the line penetration. Point 1 could not be measured due to the instruments requiring ambient semi-dry sample.

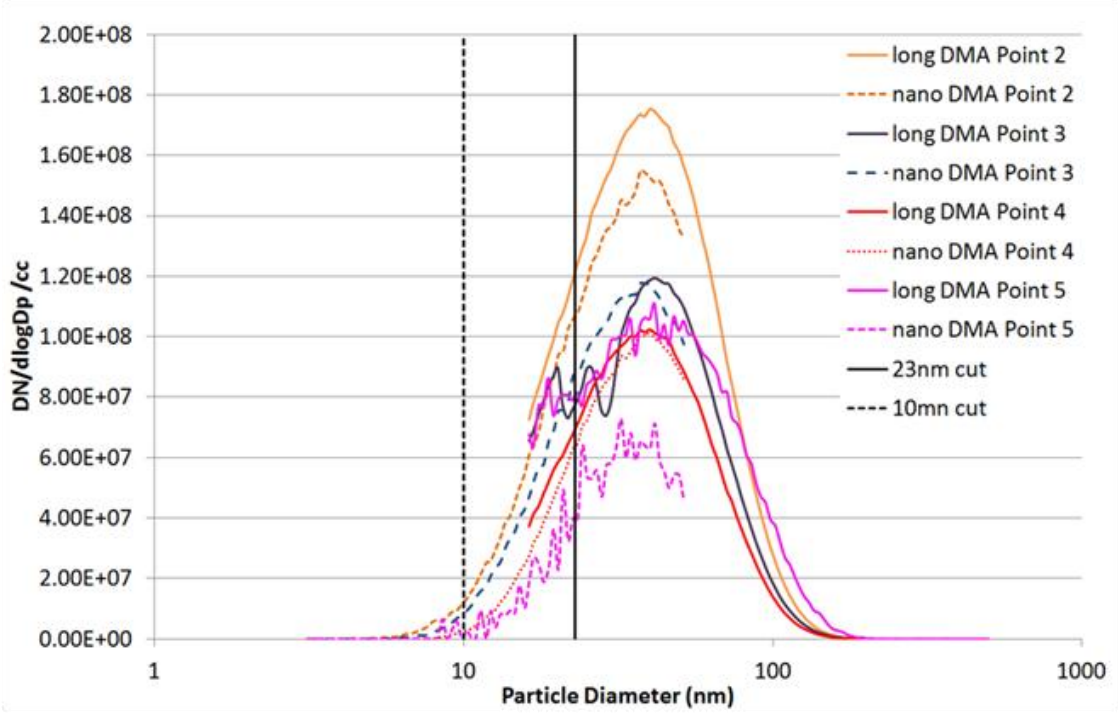


**Figure 68 SMPS (+CS) distributions obtained along sampling system of APU exhaust at Full power condition**

It can be observed once again that the vast majority of the particle loss is between Point 2 and 3 i.e. along the long 25m heated PTFE line. The ratios of the nano-SMPS size distributions to obtain sample line transport efficiencies are shown in Figure 69. In addition the, comparison against the theoretical penetration at full power condition (when the thermophoretic loss is taken into account from the CS) shows that there is good agreement between the transport efficiencies even when including the additional sampling section between cyclone inlet and CNC inlet.

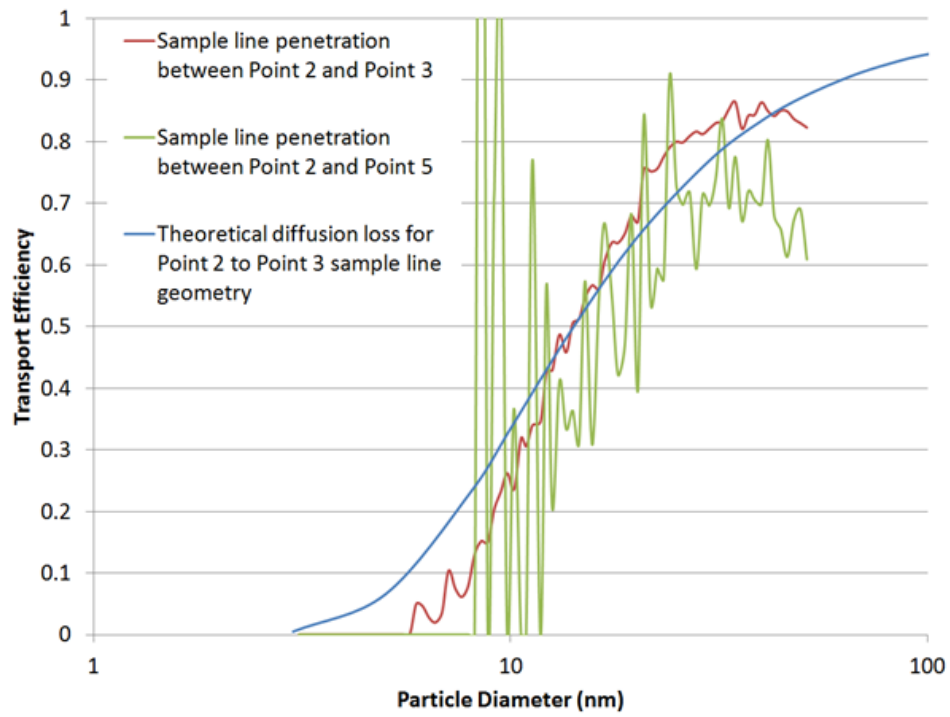


**Figure 69 Comparison of experimental (SMPS) and theoretical particle transport efficiency at full power condition**

## 6.4 Conclusions of Task 3a

1. Sheffield Universities Artouste APU is a suitable vehicle for the repeat testing required to validate a sampling system.
2. The use of the proposed sampling system utilising an eductor type primary diluter has been successfully demonstrated on a low thrust full scale APU engine.
3. Losses in terms of PM number and size have been measured along the consortium designed a built (SAE E31 Committee) proposed PM sample line length, with good agreement being observed when compared against theoretical thermophoretic and diffusion models.
4. Measured penetration data provides evidence that the transport efficiency of the consortium built (SAE E31 Committee approved) proposed sampling system can be approximated to theoretical calculations for the long 25m PTFE heated line and that as long as the sampling system is kept within 1.5m downstream of the cyclone outlet the additional particle losses are negligible.

# 7. Task 3b: Full Scale Certification Engine Testing

## 7.1 Full scale certification engine testing at R-R

During the SAMPLEIII SC01 contractual period, three large full scale certification or near-certification engine tests occurred at R-R Derby test beds. One occurred early in 2011 (February) which was outside the planned window of testing (May to September) therefore Task 2 had not been performed and consequently no sampling system was available and in addition PM instrumentation was also not available. Another test occurred late May 2011 and another in early June 2011.

For the May 2011 engine test, non-volatile mass instrumentation (LII-300) was installed in time for the test period and there was a possibility of installing a PM dilution system. However, unfortunately the emissions rake encountered sampling problems during the initial performance engine test causing the test to be abandoned.

A full-scale certification-type engine test was conducted at Rolls-Royce Derby on the 9$^{th}$ June 2011. Due to the date coinciding with that of the SAE E31Committee annual general meeting in Ottawa there was limited manpower resources available from the SAMPLE III consortium to conduct full dilution PM measurements, this coupled with the fact that most of the sampling system and analysers had already been packed/shipped in preparation for the scheduled Sheffield University APU testing (20$^{th}$ June).

A further certification-type test was planned for September 2011 but unfortunately this test has been currently re-scheduled for January 2012 (at INTA in Spain).

The consortium did everything reasonably possible to attempt to measure particulates on an existing certification-type engine test at R-R with substantial time and effort (and therefore associated cost) spent in attempting to plan and coordinate a possible test. But unfortunately, ultimately, the consortium was unsuccessful in obtaining non-volatile PM measurements on a full scale certified engine test during the course of SC01.

Unfortunately no specific SAMPLEIII-owned instrument hardware exists for sole SAMPLE III use. Hardware that exists within the consortium, or can be rented, is only available singly and for specific time periods. These reasons mean that when full-size engine tests occur, availability of certain instruments is on an ad-hoc last minute basis and often are not available at such short notice.

Engine particulate testing at R-R requires both expert and specific manpower (including currently Mark Johnson) and in addition is instrument resource dependent. If one or other is not available then supporting PM measurements on an R-R engine test is currently not possible

## 7.2 Design and installation of measurement capability to perform future full scale certification engine testing

Due to the frustration of unsuccessfully implementing the PM sample line concept and obtaining non-volatile PM measurements earlier in 2011, R-R has worked towards having a placeholder capability such that a standardised SAE E-31 Committee sample line concept can be brought to the facility and installed with minimal impact. This permits large full-scale certification-type engine tests to occur with a minimal requirement of expert manpower resource. Consequently specific personnel would not necessarily be required and at least some limited PM data (instrument resource dependant) could be obtained whenever a full size engine emissions measurement takes place anywhere in R-R Europe (Derby, Dahlewitz, INTA).

In previous SAMPLE & SAMPLE II engine test campaigns the interface between the sampling line, the existing ICAO Annex 16 system and the instrumentation were bulky, individually controlled and operated by specific personnel outside the R-R emissions van (Figure 70).

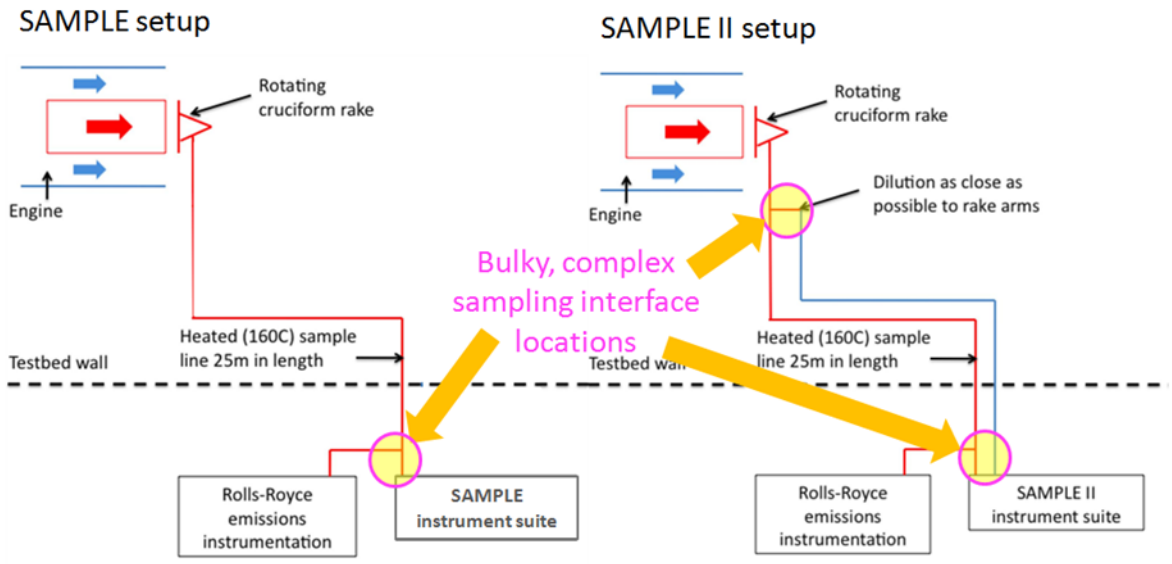


**Figure 70 Schematics of the sampling setups used in SAMPLE & SAMPLE II showing locations of complex, manpower intensive sampling interfaces**

Designing simplified sampling system interfaces in the two required locations (as shown in Figure 71) allows reduction of specific personnel resource on a PM emissions engine test and helps the planning and coordination process in terms of defining a specific test location.

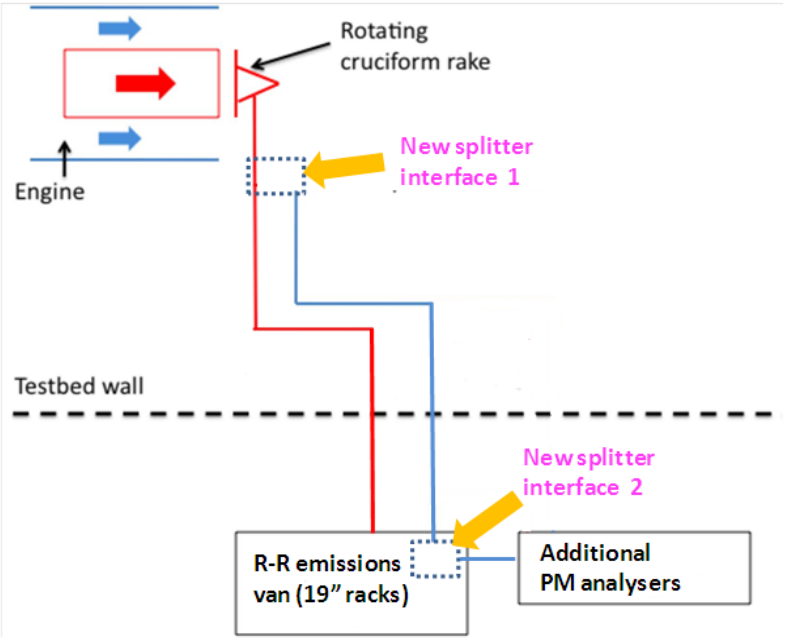


**Figure 71 Schematic of location of new sampling interfaces**

In order to provide a simple sampling interface inside the R-R emissions van that could be operated by current R-R emission measurement technicians, the design of 2 new splitter interfaces was required as highlighted in
Figure 71.

A schematic of the design for the new unit (splitter interface 1) required to split the PM sampling system from the current Annex 16 line is presented in Figure 72.

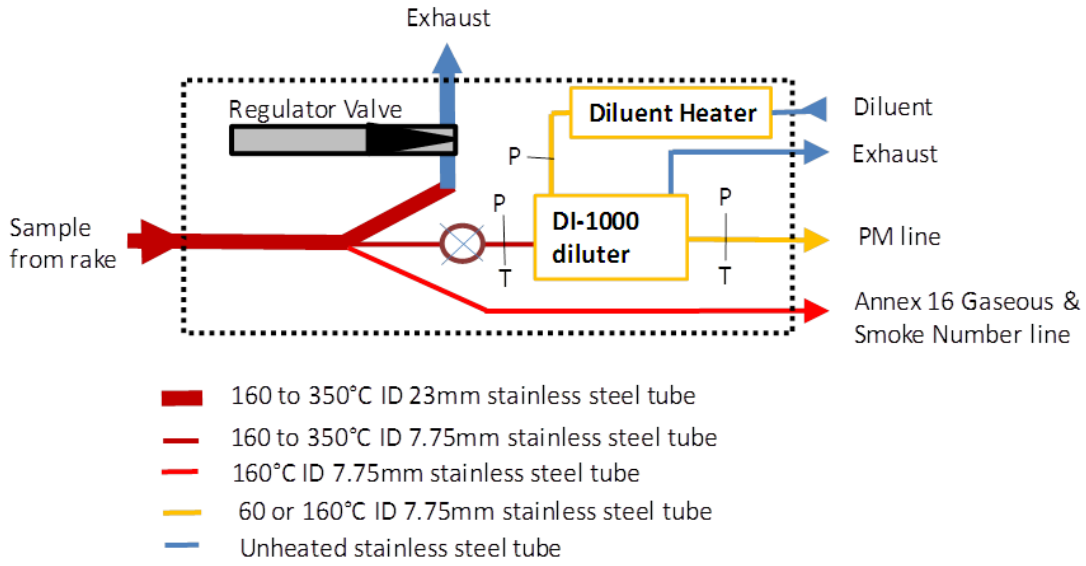


**Figure 72 Schematic of design of new splitter interface 1**

It can be seen that this splitter interface sits between the current Annex 16 compliant sampling rake and the two sampling lines (Annex 16 Gaseous & smoke and non-volatile PM). The remotely operated unit incorporates a heated Dekati DI-1000 diluter with numerous pressure and temperature measurement points along with a pressure regulating spill valve and PM sampling line isolation valve. This ensures that if required the non-volatile PM line can be totally isolated from the certified Annex 16 sampling system thus not impacting on future certification gaseous and smoke measurements.

The design and manufacture of a PM sample splitter unit (splitter interface 2), which could incorporated within the existing Rolls-Royce emissions test van was a complex task. SAMPLE III SC01 facilitated the design, whilst R-R provided the hardware and installation of the system into its emissions van to help aid this task in future engine tests.

The splitting of a single exhaust sampling line into five separate lines following the existing specifications of the SAE E31 Committee concept system was required. Four of these lines are available for the connection of PM or gas analysers, whilst the fifth is permanently connected to a filter holder (meeting existing ARP1179c protocols), which allows particulate samples to be collected on a filter (for example, Quartz for OC/EC analysis). All the pipework is heated to prevent PM sample loss and housed in a rack mountable enclosure. The enclosure features manual controls for selecting sample outputs and a specifically set each instrument flow rate. In addition, a meter is installed to automatically meter the sample through the filter holder and mass flow measurement device.

The complex pipework arrangement was modelled using computer aided design (CAD) to ensure the pipe arrangement could be accommodated within the 19” rack width. Of particular importance was the need to use a minimum 10 bend pipe radius (80mm for 8mm ID) throughout whilst trying to minimise the length of pipe and size format of the unit. The use of CAD was therefore an essential step to ensure a successful system. The initial CAD model concept is shown in Figure 73, however, note that the detail of the bespoke 5-way 30° particle splitter is not shown.

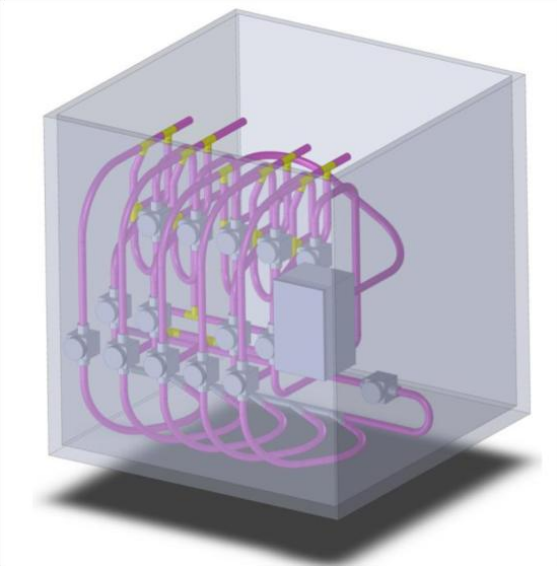

**Figure 73 Initial CAD model of pipework layout, used to determine the feasibility of installing a system in a confined area**

On completion of the design a two part 19" rack mountable instrument stack was developed. This console, (splitter interface 2) houses the heated sampling section (4PTSc) including the cyclone and also facilitates PM sample flow control and metering to several PM and $CO_2$ measurement instruments.

Photographs of the front and back of the Rolls Royce commissioned console system are shown below in Figure 74.

A separate 3-channel heater controller (mounted above the splitter interface) allows control of the inlet sample line, the split sample lines and the smoke filter line. This affords individual temperature control of each of these three groups to a user defined temperature, of up to 200°C. Thermocouples mounted on these lines are connected from the piping unit to the heater control via panel mount sockets mounted on both units.

**Figure 74 The front and rear panel of the console system with heater controller**

The front panel contains the filter holder along with valve controls, which allows selection and flow control of each of the sample lines splitting from the main sample inlet. Pressure gauges monitor line pressure and surplus flow can be removed through dump valves. Rotameters on the sample lines (plumbed in downstream of instrument) allow the user to control and monitor the sample flow through each line.

On the rear of the console there are two sample inputs:

(i) Direct input of the standardised sample line
(ii) Input via a 1µm cyclone of the standardised sample line

There are four sample outlets to be utilised by measurement instruments for:

(i) Non-volatile PM mass

(ii) Non-volatile PM number (via a volatile remover)
(iii) $CO_2$ analyser for eductor dilution ratio measurement
(iv) PM size (if required)

The counter for controlling the sample flow through the filter holder on the front panel uses a reading from a coriolis mass flow meter connected to the filter line exhaust. This provides either

(a) a metered flow to create the fixed sample flow rate through the standardised sampling system

and/or

(b) a total mass of exhaust sample that has flowed through the filter. A solenoid switch valve is automatically operated, diverting flow through a bypass of the filter, when a prescribed total is reached.

Schematic representations of how the console (splitter interface 2) could be configured to carry out future PM measurements are presented in Figure 75 & Figure 76.

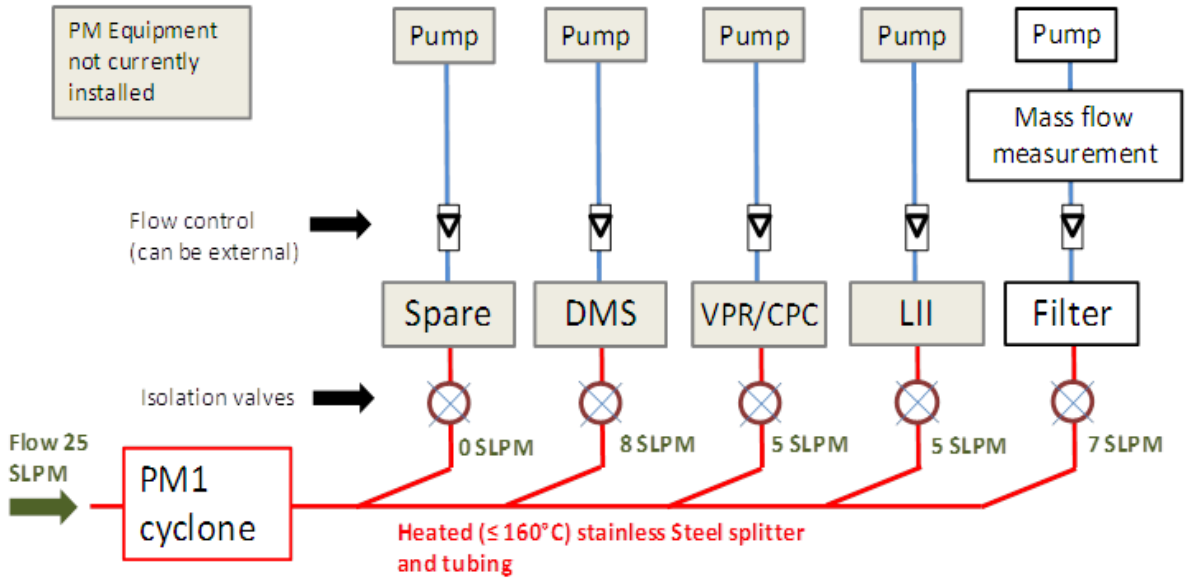


**Figure 75 Schematic representation of new splitter interface 2 configured for a 'standard' proposed non-volatile PM measurement**

As can be seen (Figure 75) a ‘standard’ SAE E31 Committee non-volatile PM experiment could be conducted with the addition of a DMS or other size measurement instrument and filter if required for validation of results.

Similarly the unit could be configured to facilitate a mass instrument inter comparison study as is currently highlighted as necessary by the SAE E31 mass team. A schematic of this configuration is presented in Figure 76.

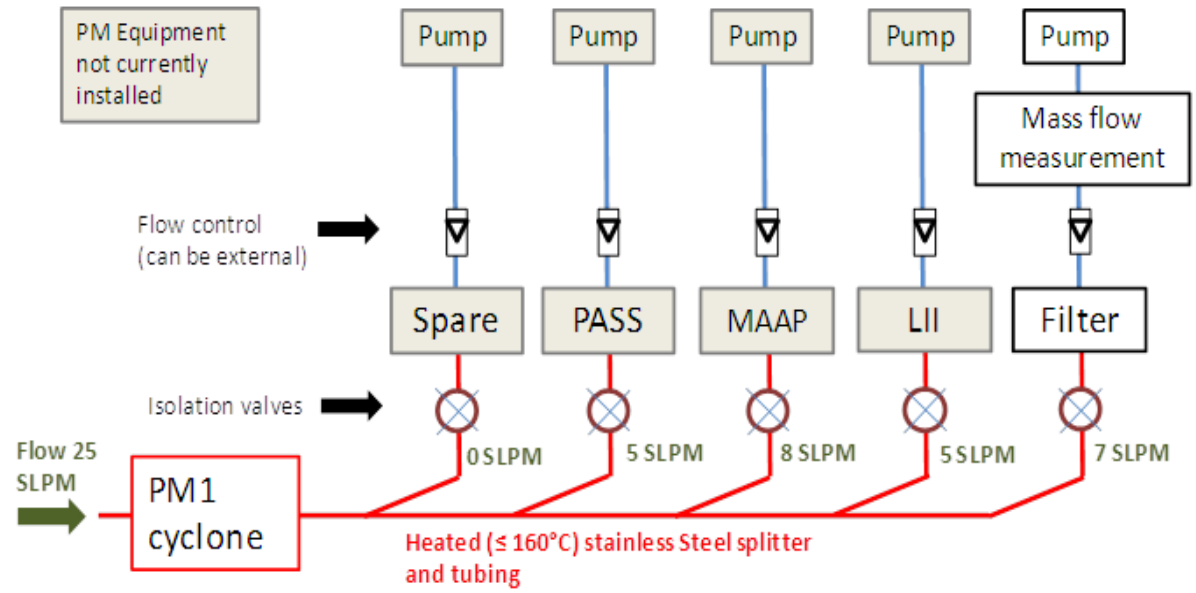


**Figure 76 Schematic representation of new splitter interface 2 configured for a mass instrumentation inter comparison study**

This system has been fully implemented into the existing R-R emissions van, however at present only a filter based particulate sample could be guaranteed as R-R do not currently have installed any of the numerous PM measurement instruments.

In addition to the design of the two splitter consoles, there has been further work to implement the installation and operation of an SAE E31 sample line concept with minimal manpower requirements for PM measurements. Hardware and software alterations have been identified, designed and modifications implemented to notionally create a simple interface to attach and make PM measurements using a standardised SAE E31 sample line concept.

Rolls Royce having invested significant effort into implementing the designs conducted by the consortium for this task are fully committed to taking non-volatile PM measurements during upcoming test campaigns (subject to instrument and consortium built sample line availability). Suitable non-volatile PM data collected during the SAMPLE III Framework timeframe will thus be made available to the SAE E31 Committee via EASA.

## 7.3 Conclusions of Task 3b

1. The provision of the two simplifications of the sampling interface discussed in 7.2 will enable provision of non-volatile PM measurements on any future large full-scale certification-type engine test in R-R Europe assuming that an SAE E31 sampling concept standardised system is available
2. Throughout 2011 there has been and will still continue to be, good communication between consortium members and instrument rental manufacturers. If future funding and EASA still require full-scale modern engine testing, R-R are committed to provide PM testing opportunities and support, and the consortium will do everything reasonably possible to try and get PM sampling and measurement instruments to a certification-type engine test when one next occurs at RR Derby, Dahlewitz or INTA.

# 8. Task 3c: In-Service Non-Certification Engine Testing: Feasibility study.

## 8.1 Scope

The SAMPLE III experimental parties will not perform in-service engine sample line validation studies due to the time frame and budget of the Specific Contract No.1 proposed by the Funder. As an alternative, MMU will perform a feasibility study, develop collaborations and finalise costs with service maintenance facilities and other engine manufacturers in order to develop a fully costed proposal. Such a proposal may then be used by the Funder or the Parties to secure additional funding to perform the in-service engine sample line validation studies.

## 8.2 Task Overview

In this task the opportunities and prospect for in-service non-certification engine testing at off-wing engine maintenance and manufacture test facilities are assessed.

Contact and site visits have been made to GE Aircraft Engine Services (Cardiff), SR Technics (Zurich) and Rolls Royce (Derby) to assess the possibility of an off-wing emissions measurement site for in-service or production pass-off engines. All test facilities are of a similar general design with the engines being centrally mounted numerous metres from the test bed floor in a cell of a double concrete wall construction. The size of the test cell depends upon the fan diameter and non-emission related testing (eg fan blade off, water ingress, etc).

Negotiations with these companies with the aim of developing a working relation as potential SAMPLE III measurement sites have been explored. Details are given as case studies within the report. A preliminary paper study has also been considered for GE Caledonian (Prestwick). Contact with this later site has not been made at this time. It was considered that the only collaborative program between the SAMPLE III consortium and GE could have been jeopardised by negotiating with two GE subsidiaries simultaneously.

At this time, the development of a fully costed accurate proposal is not possible since details of the PM sampling probe and details of the experimental configuration required by the funder have not been specified. Nevertheless, a table of cost estimates has been included based upon best estimates from other sources. Experimental running costs for off-wing in-service engine testing are likely to be similar to those previously encountered for certified engine testing, however it should be noted that sizable ‘one off’ set up costs will be required to provide existing test beds with suitable bespoke measurement probes and sampling lines which will be discussed in detail later. Fuel costs are often sizeable and so it is recognised that coordinating emission tests that run in conjunction with pre-existing standard third party engine testing to eliminate these costs is desirable. Equipment usage costs may however become appreciable when used in a semi-permanent installation, as these items are no longer available to consortia partners to support the fulfilment of other contracts. Equally, equipment rental costs for long-term usage may become prohibitive and equipment purchase should be considered by the funder. Probe design and installation costs are probably the largest single expenditure within the current proposal. This cost item is common to most of the facilities considered with the exception of SR Technics which has already been fitted with a bespoke single access traversable probe funded by the Swiss government, and although the precise magnitude is difficult to gauge and is likely to vary between facilities

this example gives a good 'benchmark' to base a cost model on. The installation of a PM sampling probe at any one of the facilities must be considered as a bespoke engineering project that does not lend itself to detailed costing as there are many unforeseen difficulties. Furthermore, the capital investment required for the design and installation of a suitable PM sampling probe is unrecognisable as an auditable asset, as its cost far exceeds the value of its component parts. However, the relatively high cost of the probe may be reduced by design collaboration with FOCA and this one-off cost must be considered in terms of the multiple measurement opportunities that may be realised, albeit with a limited number of engine types at each of the individual test sites considered.

It is estimated that off-wing non-certification engine testing would be feasible on a timescale in the region of six to twelve months after the design and construction of the probe and sampling system. However, in the case of SR Technics (Zurich) this time maybe shorter as a successful demonstration of the facility has already taken place.

## 8.3 Introduction

The current requirements for aircraft engine emission certification do not include a direct measurement of particulate matter (PM). The closest parameter that is certified is the Smoke Number (SN). Smoke number was however, developed as a useful metric to mitigate the visual impact from aircraft emissions. It is an inappropriate metric for assessing the impact of PM on human health and climate change. Current understanding of PM indicates that measurements of the mass, number and size loading are needed to quantify the environmental and human health impact of aircraft emissions.

The SAE (Society of Automotive Engineers) E-31 committee is developing sampling and measurement techniques for the characterisation of non-volatile PM emissions from aircraft engines. This has resulted in the publication of the Aerospace Information Reports: AIR5892 (2004) and AIR6037 (2010). However, further development of the information in these reports is necessary before an SAE Aerospace Recommended Practice (ARP) containing a step-by-step detailed application of the techniques for a future PM emissions certification requirement can be made.

The Committee on Aviation and Environmental Protection (CAEP) within ICAO expects that a non-volatile PM standard could be developed by the end of 2016. For this reason, the regulatory agencies have requested the SAE E31 Committee to provide a ballot ready non-volatile PM mass and number ARP by February 2013. This ARP development will require inputs from regulatory, standards, research and industry communities.

## 8.4 Specific objectives of Sample III in-service engine testing

The main objective of in-service engine testing is to gather information regarding aircraft engine non-volatile PM emissions and contribute to the development of the ARP for non-volatile PM emissions measurement. It is expected to include work associated with the following tasks:

Primary:

- execution of engine tests and/or combustor rig tests to assess the validity of the sampling and measurement methodology for certification conditions;

Secondary:

- develop solutions to answer outstanding technical questions on the development of a sampling and measurement system;

## 8.5 Measurements and supporting data for in-service engine testing

The prime goal of the SAMPLE III program is to draw together the data necessary to develop an ARP for non-volatile particulate matter. Previous SAMPLE programs have focused on the sample line and instrument validation studies principally with the Hot End Simulator (HES), although supported with some limited engine certification testing at Rolls-Royce, Derby.

In-service engine testing is an important step in the progression and development of an ARP for non-volatile PM sampling as it provides access to a large number of current fleet engine tests over a short time frame, when compared to the sparse access provided by engine certification facilities on development and new technology engines. Realising non-volatile PM measurements on these tests will ensure that the SAE E31 Committee methodology is practical, useable and robust. The ARP must be broadly applicable to modern in-service civil aircraft engines types and appropriate to certification and non-certification engine and combustion rig testing.

Current understanding of PM indicates that measurements of the mass, surface area, number and size loading are needed to quantify the health and environmental impacts of aircraft emissions. However, the proposed regulatory requirements are to quantify non-volatile PM mass and number only. Consequently, measurements on in-service engines must specifically focus on these latter measurements, although where possible the measurement of other parameters are also desirable as it adds research value to the overall program particularly in terms of defining PM line loss. Value added research will be at no additional cost to EASA.

The exact instrumentation deployed on an experimental measurement campaign is dependent upon the specific objectives, the availability of equipment, the availability of manpower and the overall budget. A detailed description of the instrumentation available has been given in the SAMPLE II report and so is not discussed here. A summary table of the instrumentation that is potentially available within the SAMPLE III consortium is given in Appendix A.

However, in taking emission measurements on new, used, repaired or reconditioned in-service aircraft engines it may also be important to obtain supporting information to contextualise the data obtained. The combustion of fuel in a gas turbine engine is a highly efficient process. Nevertheless, there is little evidence to assume that the emissions will be identical to the emissions when the engine was first certified. Inter-engine variability of PM emissions will occur, and characterising this variability is a complex task. In commercial carrier operations, fuel flow is sometimes used as an indicator of engine performance, deterioration and for broad categorisation of inter-engine variability. However, the variability and uncertainties in in-flight fuel flow measurement are high and could correlate poorly in relation to the emission of PM. Hence other supporting metrics may be required.

The level of detail in the supporting information is dependent upon the specific experimental objectives. Supporting data may include exact engine type, year of manufacture, engine operational hours, fuel flow and service history, all of which may be considered to be commercially sensitive.

Ultimately, for uncertainties in the sampling or measurement technique to be identified and characterised, the uncertainties and emission variations between different in-service engines must be accounted for.

## 8.6 Legal requirements: Permissions from engine owners

Carriers and aircraft engine owners recognise that branding is an integral part of their business model. Off-wing engines that have been sent for maintenance at a specialist facility have been done so in good faith. And it has been highlighted engine maintenance facilities will recognise and respect their client interests above the interests of the SAMPLE III consortium. It is unlikely that maintenance facilities will allow access to engine testing or supporting data without the direct written consent of the engine owner. Clarification on this matter will be required for each individual facility, although GE Aircraft Engines Services (Cardiff) have confirmed that this would be their position. For production pass-off facilities (i.e. at Rolls-Royce Derby) this may not be the case, but this is still to be confirmed.

Attaining permission will probably require negotiation with each individual carrier/owner, although this task may quickly become less problematic after an initial core number of agreements have been established. For example, considering the breakdown of engine ownership at GE Nantgarw (20% BA, 35% Emirates, 15% Ryanair/Easyjet, 10% Air France) it would be most productive to approach BA with whom members of the consortia already have strong working relation in the first instance. Once an agreement has been made with BA it is unlikely that other carriers will have significant objections. However, in this task a reassuring letter of support from EASA would be very helpful. An information sheet that specifies how the data will be made anonymous, used and distributed will also be necessary. A suitably drafted non-disclosure agreement may also be appropriate.

Attaining permission from engine owners is good practice, defines the terms by which the data can be used and thus mitigates against possible future litigation. Engine owners may also have the opportunity to benefit from the feedback of engine emission data from the SAMPLE III consortium.

## 8.7 Legal requirements: Insurance

All consortium staff and subcontractors will by nature of their employment have third party insurance for their work. For university based researchers this typically amounts to €5 million. Operation of a sampling probe behind an off-wing engine in a manufacturing or maintenance facility may however carry additional risk as tests are performed within a nominally closed environment: Aircraft engines represent a significant capital investment and deliveries often operate to a well defined schedule. Should the probe break away and cause damage that renders the test cell in need of repair, this schedule may be disrupted and engine late delivery penalties may be applicable.

Consequently, additional insurance at additional cost may be necessary for engine test cell measurements. Clarification with individual facilities will be required once equipment, risk assessments and method statements have been finalised.

## 8.8 Opportunities for in-service non-certification engine testing

In principle, there are a considerable number of opportunities for in-service non-certification engine testing. However, individual facilities generally specialise in just two or three specific engine types and so to obtain data from a range of different engine types would require engine testing at more than one facility (a summary of all in-service engines is given in Appendix C).

Access to the engines within a specific facility may require an appreciable amount of direct negotiation with both the facility management and engine owners. In addition method statements that are compatible with the working practice at each facility would be required.

Table 23 lists a number of potential non-certification engine testing facilities at locations across Europe together with the engine type in which they specialise. (For a more exhaustive list refer to *www.aviation-database.com*).

**Table 23 List of potential non-certification engine testing facilities across Europe together with the principal engine types at these locations**

| Facility | Location | Engines | Notes | Potential opportunity |
|---|---|---|---|---|
| GE Aircraft Engine Services | Cardiff | GE90, GP7200, RB211, CFM56 -3/ -5/ -7 all variants | 2 test-cells probe req. | 450 engines per year |
| GE Caledonian | Prestwich. | GEnx, CF6 | 1 test-cell probe req. | 150 engines per year |
| SR Technics | Zurich | CFM56-5B/ -5C/ -7B, PW 4168 (100") PW4000 (94") | 1 test-cell probe installed | 260 engines per year |
| SNECMA Services | Paris | CFM56-2/ -3/ -5/ -7, GE90, JT8D, JT9D | 1 test-cell probe req. | 150 engines per year |
| SNECMA Sabena Engine Services | Brussels | CFM56-3, CFM56-2, CFM56-7B | 1 test-cell probe req. | |
| MTU Aero Engines | Hannover | CF6-50, PW2000, V2500, CFM56-7B | 1 test-cell probe req. | |
| MTU Aero Engines | Berlin | PT6A, PW200, PW300, PW500, CF34 | 1 test-cell probe req. | |
| Rolls Royce | Derby/ Dahlewitz | All RR engines | 5/2 (prod) test cells probe req. | Production 500 per year |
| Lufthansa Technik Airmotive | Ireland | CFM International, PW engines | 1 test-cell probe req. | |

Note that in contrast to the facilities considered herein, on-wing testing of in-service engines has occurred in a number of high profile studies since 2004 within the US. The results of these studies have been fed into the E-31 committee via Phil Whitefield of Missouri Science & Technology University. Studies of note include: APEX (2004), APEX2 (2005), APEX3 (2006), AFFEX (2009) and AFFEX2 (2011). In these studies on-wing testing is preferred to off-wing as this has the additional benefit of enabling plume aging effects to be studied at downstream distances of up to 50 metres. However the experimental objectives and scope of the work in these studies was much broader than those considered for the SAMPLE III program. In such cases, the studies were aimed at scientific investigation, rather than the specific development of a measurement protocol or standard.

## 8.9 Case studies

### 8.9.1 Case study: Off-wing engine testing at GE Aircraft Engine Services, Cardiff

Contact: Adrian Button (MD)

Jonathan Lucas (Head of technical, 01443847735)

At GE Aircraft Engine Services it takes up to 45 days for an aircraft engine to be completely overhauled depending upon the size and scope of the work. The facility at Cardiff principally deals with the GE90, GP7200, RB211 and CFM family engines, details of the specific engines are detailed in Table 24. Total throughput at the plant is approximately 450 engines per year. Throughput on an engine-by-engine basis is as follows: GE90 (250 engines), CFM -3/ -5b/ -5c/ -7b (120 engines), GP7200 (30 engines), RB211 (50 engines). At this site there are two state-of-the-art enclosed test cells which are used to ensure that engines can go back into service immediately once returned to the customer.

**Table 24 Selected data for the engines available at the GE engine maintenance facility**

| Engine type | Diameter (inches) | Max. Thrust (lbf) | Application |
|---|---|---|---|
| **GE90** | 134.0 | 67 000 – 115 000 | B777 |
| **GP7200** | 124.0 | 70 000 – 77 000 | A380 |
| **RB211** | 84.8 / 85.8 / 86.3 | 40 000 – 61 000 | B747 / B757 / B767 |
| **CFM56 -3** | 60.0 | 18 000 – 24 000 | B737 |
| **CFM56 -5B** | 68.3 | 22 000 – 33 000 | A319 / A320 / A321 |
| **CFM56 -5C** | 72.3 | 31 000 – 34 000 | A340 |
| **CFM56 -7B** | 61.0 | 19 000 – 27 000 | B737 |

GE Aircraft Engine Services apply a business model that is built upon delivery of a quality service that is highly customer focused. Engine testing operates to a defined schedule and operational efficiency is carefully managed in order to minimise fuel usage and expenditure. GE operate a policy that steers away from customer scoped work in order to maximise yield and guarantee quality, although some pass-off testing for external customers who perform their own maintenance is also undertaken (Air France). Engines that pass through the test cells having undergone maintenance have a 97 percent yield.

The SAMPLE III consortium has commenced some initial discussions with GE Aircraft Engine Services, Nantgarw, on the possibility of making emission measurements in one of the test cells during engine break-in testing. Through these discussions, the company have stated that they are not engaged in research and currently see the opportunity to feedback measurement data to engine owners as limited. Nevertheless, they would have an appetite to work with the SAMPLE III consortia but this would be subject to agreement from central office and approval from engine owners would be required. Their motivation for participation in the project is more aligned with the promotion of GE as a quality brand with a proactive involvement in the broader aviation community.

At GE Nantgarw approximately 80 - 85 percent of engines that pass through the plant will undergo break-in testing prior to performance testing. The remainder will undergo simply pass-off testing having been subject to relatively minor overhaul (such as work to resolve vibration issues). This is appreciably higher than the initial estimate, based upon information from SR Technics, which suggested that up to half of all engines passing, require break-in testing.

During break-in testing, engines are progressively ramped up in defined steps from idle to full power and back to idle. Information from FOCA's experience in Zurich suggests that each power step is stabilised for limited time (>5 min at idle, 3.5 to 5 min at higher thrust settings) and the whole sequence takes a little in excess of an hour. Information from GE at Nantgarw suggests the break-in period for GE90 engines can be up to 4 hours and covers a range of steady states of up to 20 minutes as well as transient conditions. Similarly the break-in period for RB211 engines can be up to 3 hours. GE Nantgarw are currently considering to what level precise information on the test sequencing is proprietary before sending it to the SAMPLE III consortia for inclusion in this report.

Engines that have undergone major overhaul must also undergo performance testing in which accurate thrust specifications are determined. GE Nantgarw is presently undecided as to whether a PM sampling probe would be permissible behind the engine during these tests. However, recent comparative tests conducted at SR Technics with a CFM56-5C engine at idle and at maximum continuous thrust condition during data acquisition testing, with and without the FOCA probe in the exhaust stream have demonstrated that there is no measurable variation in the engine data derived (e.g. there is no measurable thrust change from extended to retracted probe at max. continuous thrust for that engine in this installation). This result was not expected. SR Technics plans to repeat this test with the other engine types measured to validate any questions that may be asked about the influence of the probe. Nevertheless, SR Technics is cautious and no sampling with the probe in situ is done to date during performance certification related engine runs.
Rolls-Royce stated that they would need to conduct similar experiments to allow sampling during normal testing cycles. Thus it is prudent for the SAMPLE III consortia to presume an equally cautionary approach from GE. Consequently, the affects of any installed PM sampling probe would need to be fully appraised (which may require extra funded engine test time) and remotely retractable during the testing cycle to ensure conformity within the test cycle.

At GE Nantgarw, test cell No.1 is currently used exclusively for the testing the CFM family of engines although it is intended that RB211 engine testing will be moved there in the near future. The larger test cell No.4 is currently used for GE90, GP7200 and RB211 engines. Hence test cell No.4 is in appreciably greater usage (330 verses 120 engines per year) and it was indicated that the installation of a probe in (the less busy) test cell No.1 could be better

accommodated. However, this would only give access to similar engine variants as available at SR Technics (Zurich).

Operation at test cell No.4 is almost continuous with engine testing around the clock on a 24/7 basis. Outside of this state-of-the-art test cell there is little or no audible evidence that an engine is running within, even at high power as is the case with all the facilities visited. The operation of a PM sampling probe within this test cell may be possible but would require the seamless integration into the current testing schedule. Delays to the engine test schedule would not be acceptable as customer focus is a priority. If 330 engines are envisaged per year, each requiring a cautious upper estimate of 8 hours test cell time, then with careful planning there is still sufficient time for the initial installation of a sampling probe without disruption to the test schedule.

For both test cells, engines are brought in from the adjoining final module assembly workshop into the test cell on a ceiling mounted mono-rail before being lowered into place on the test cells engine thrust frame. At the rear of the engine a connection plate is hydraulically advanced into position that serves to link all connections (fuel, electrical, control, etc). All systems on the connection plate are self connecting so that engine installation is achieved in approximately 20 minutes. Engines in the test cell are well instrumented and many key engine parameters are routinely recorded (including N1, N2, N3, temperatures, fuel flow, etc) providing valuable support data.

The test cell control room is situated adjacent to and at the same level as the engine and there is a maintenance room situated above the engine. The maintenance room has power and would probably be suitable for the installation of the approved non-volatile PM measurement equipment. A trap door exists between the test cell and the maintenance room through which the heated line could be passed. In this configuration, the distance from the probe head to the measurement suite would be typically less than 10 metres. However, the viability of this option would need to be further investigated.

Should the project go ahead, members of the SAMPLE III consortia permitted to work on site would be treated as contractors. As such equipment and gases would be allowable on site subject to the submission of accompanying and suitably detailed COSHH and risk assessment documentation.

The optimum position for the PM sampling probe has yet to be determined. The installation of a PM sampling probe is a bespoke engineering project that would require detailed consultation between the off-site probe designer (probably GE Aero) and the GE on-site engineering department. However, initial thoughts are that the engine mounting frame or the ceiling mounted thrust frame may offer suitable locations. Whilst there is an elevating floor section beneath the engine, this is fully lowered during testing. The MMU traverse probe would not be suitable for use at this facility as there is no solid floor beneath the engine.

The engine mounting system consists of a heavy duty welded girder frame that is specific to an engine type. That is, a different frame is used for each different engine types (different to Rolls-Royce facility). At the rear of each mounting frame there is a relatively light weight framed section covered by a plated fairing. This section is approximately similar in form and dimension to the aircraft pylon section that is used to connect the engine to the wing, and it is assumed that its function is to act as a surrogate for this structure whilst the engine is under test. Hence in similarity to Rolls-Royce facility (see next section) this may be a good location to position a PM sampling probe since it is sheltered from the bypass air.

On site photography was not permitted at GE Nantgarw. However, in order to aid visualisation, the following photographs sourced from stock websites and illustrating broadly similar facilities have been included.

**Figure 77 Left: Stock image of an aircraft engine linked to the engine carrier frame (blue) and being moved on the ceiling mounted mono-rail system (yellow). Right: Stock image of an elevating floor section beneath engine in test cell for maintenance work**


**Figure 78 Left/ Right: Stock images of the tail-fairing housing that connects the engine to the aircraft wing. Note that the tail fairing must necessarily impede an area of the bypass air**

### 8.9.2 Case study: Off-wing engine testing at Rolls Royce, Derby

Contact: Mark Johnson (Emission measurement expert/SAMPLEIII)

Paul Madden (Engine emission expert)

Rolls Royce have six state-of-the-art production pass-off test cells that are potentially suitable for use with a PM sampling probe and measurement equipment: Test cells #54, #55 and #56 are used for all engine types, whilst test cells #48, #51 and #52 are used primarily for T500 and T700 series engines. In addition, the research test bed #58 that is primarily used for certification testing may also be available. In all of the afore mentioned test beds, engines are well instrumented and many key engine parameters are routinely recorded (including N1, N2, N3, temperatures, fuel flow, etc) providing valuable support data.

Throughput within these six test beds is typically 10 engines per week, and current production engine types include T500, T700, T800, T900 and T1000 with the TXWB likely to be tested in the near future, details of which are given in Table 25. Of these engine types

the T700 series mixed flow exhaust would require a different proposal than the one specified below for PM sampling.

**Table 25 Selected data for the engines available at Rolls Royce**

| Engine type | Diameter (inches) | Max. Thrust (lbf) | Application |
|---|---|---|---|
| T 500 | 97.4 | 53 000 – 60 000 | A340 |
| T 700 | 97.4 | 67 000 – 71 000 | A330 |
| T 800 | 110.0 | 75 000 – 93 000 | B777 |
| T 900 | 116.0 | 75 000 – 84 000 | A380 |
| T 1000 | 112.0 | 53 000 – 75 000 | B787 |
| T XWB | 118.0 | 75 000 – 93 000 | A350 |

Engines enter the test bed on the back of a purpose build vehicle, with a 'prod pylon' fastened to the engine and facing uppermost. The engine together with its associated pylon are then raised from the vehicle using four cables and secured in place within the test bed thrust frame. The vehicle is then removed. The test schedule for a specific engine type has yet to be confirmed but is believed to be a similar procedure as specified for GE Nantgarw and SR Technics (each specific engine type will have an exact specific procedure).

An initial assessment has indicated that PM sampling in or close to the exit plane of the core would be most effectively achieved with a vertical traversable sampling probe (either single or multi-hole giving a vertical average) which is mounted on the prod pylon. However, this is a bespoke engineering design that would require detailed consultation between the on-site probe designers and engineering department. It is unlikely that an autonomous ground mounted probe could be positioned within the test cell as this may compromise the vehicle access and like GE would prevent use of the elevating floor.

A pylon mounted PM sampling system would have the advantage that a single probe design could be used for all unmixed engine types and in any test cell. Thus keeping potential future probe installation costs down. However, this must be balanced against the potential reduction in the number of opportunities as a result of the number of engine assembly pylon in use throughout the plant: Rolls Royce have three almost-identical prod pylons for each of the T500, T800, T900 and T1000 unmixed exhaust engine types (and expected to include Trent XWB), and four for the T700 mixed exhaust engine type. This approach allows for a one-off bespoke probe design that could be then replicated and installed on one pylon for each of the unmixed engine types. Depending upon production allocation this would statistically permit the testing of a specific engine type within two months. Or any unmixed engine type within two weeks, independent of which test beds were used. This is a significant improvement over development engine emission testing of approximately one to two per annum, though this type of testing does include certification-type probe sampling.

A section of the prod pylon structure for unmixed engines has been cautiously identified as a potential location for the installation of a PM sampling probe. On the assembly pylon towards the rear of the engine there is a structure which is representative of the aircraft tail fairing section that is used to connect the engine to the wing. The function of the fairing on the assembly pylon acts as a surrogate for the aircraft wing pylon so that engine test data is better matched and representative of the aircraft operational conditions.

An approved photograph showing the tail fairing and pylon is shown below together with a sketch showing the exit plane of the engine to aid visualisation (Figure 79 Figure 80).

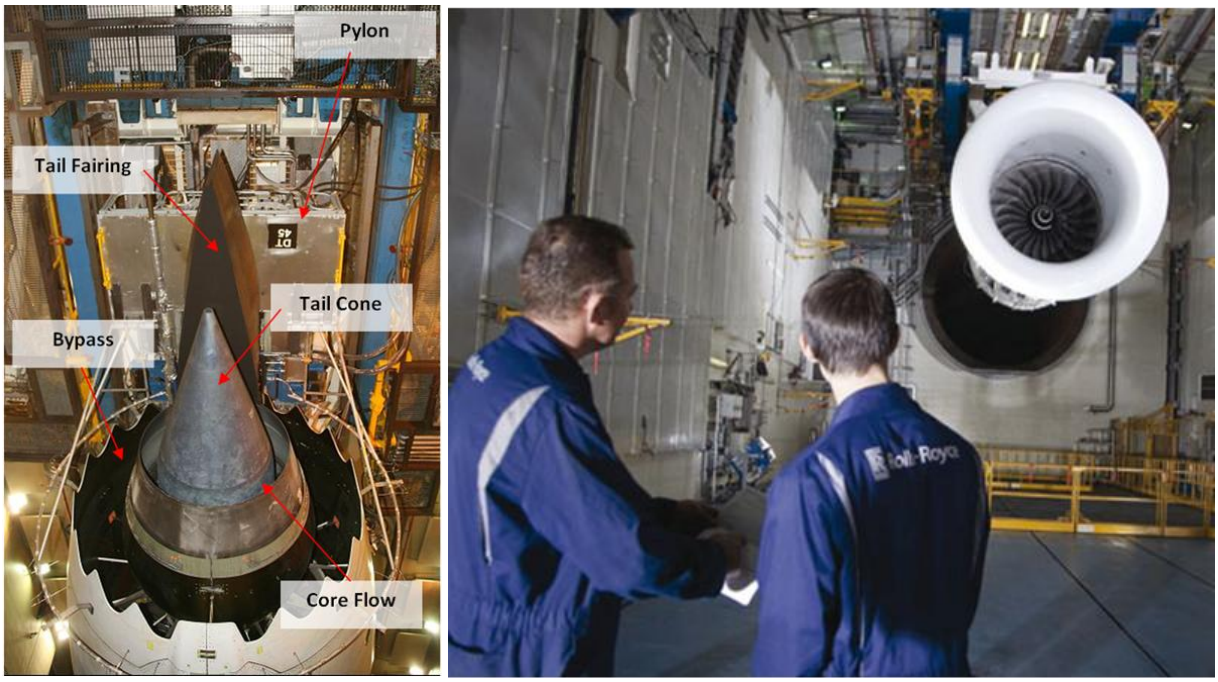


**Figure 79 Image of a Rolls Royce engine with pylon structure and example of a test cell at the Rolls Royce plant.**

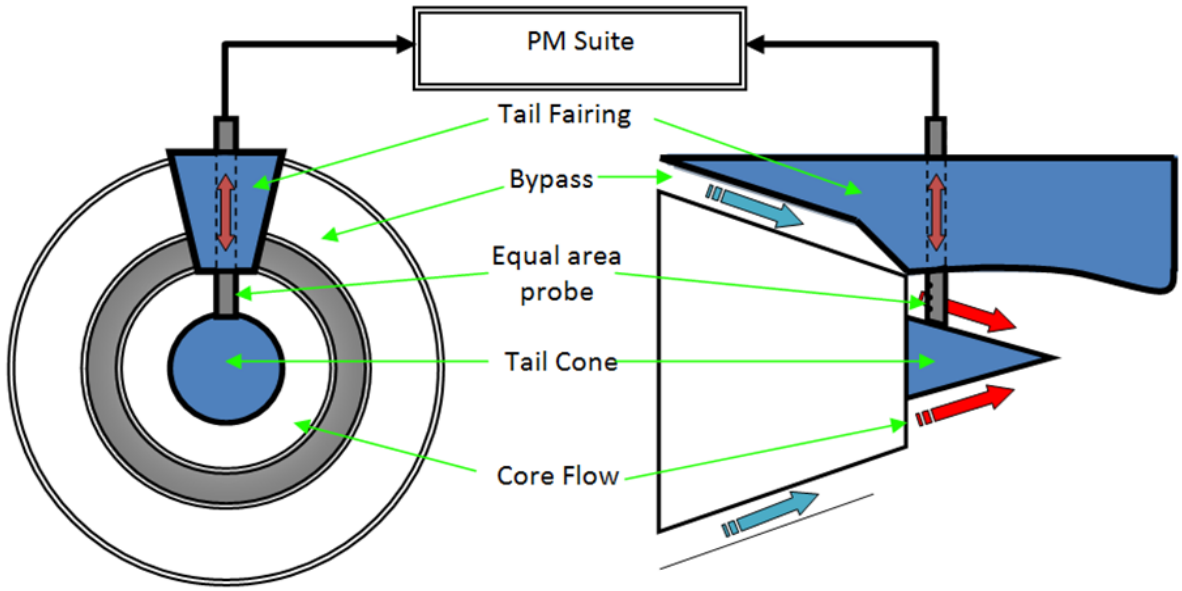


**Figure 80 Sketch showing the exit and side plane views of the engine and the position of the tail fairing section of the prod assembly pylon structure**

A PM sampling probe sited in the fairing part of the structure is inherently sheltered from the bypass air flow and so offers a number of advantages; the probe can be relatively small, the probe would require a traverse of less than 0.2m in order to be completely retracted and the probe temperature can be better maintained. The main engineering difficulty would be in sealing the fairing around the body of the probe.

Within Rolls-Royce and therefore the SAMPLE III consortium there are expert sampling probe designers who could be commissioned to better assess the feasibility of positioning a retractable probe at this location.

Senior management has given approval at Rolls-Royce to pursue and allow PM engine testing using production pass-off facilities. The exact requirements on whether permission from future engine owners is still being assessed, though so far all indications are that this will not be required.

Should the testing occur at Rolls- Royce, SAMPLE III consortium members will be treated as contractors on site and must abide by local HS&E rules. A benefit to using R-R facilities is the on-site Annex 16 compliant emissions measurement van, which can be commissioned for use within 24 hours.

### 8.9.3 Case study: Off-wing engine testing at SR Technics, Zurich

Contact: Theo Rindlisbacher (FOCA)

As discussed earlier considerable investment has already been spent at SR Technics, (by the Swiss Government Agency FOCA). As such there is already an SAE E31 Committee approved PM sampling system and traversable probe installed within the test bed as shown below in Figure 5. However, it should be noted that the current probe is a single point 1-D traversable probe (with the potential of adding the second traversable dimension) and is therefore not representative of the whole engine core exhaust. The current installation is not intended for measuring a representative sample and therefore cannot map the emissions characteristics of the tested engines. The probe provides a sample at repeatable positions, selected according to the need of attaining certain concentration levels and pressures to test a PM measurement system. Thus, the probe at present is not compliant with current certification methodology owing to the aforementioned reasons coupled with the fact it is positioned outside of half a nozzle diameter of the engine exhaust for some engines (e.g. for the -7B it is inside).

Notwithstanding the above this facility could immediately offer a potentially economically viable option to conduct preliminary testing of the proposed SAE E31 Committee concept sampling system (which starts from the first dilution point (Figure 46)) behind four current technology in service engine types (as detailed earlier (up to 100” Fan diameter).

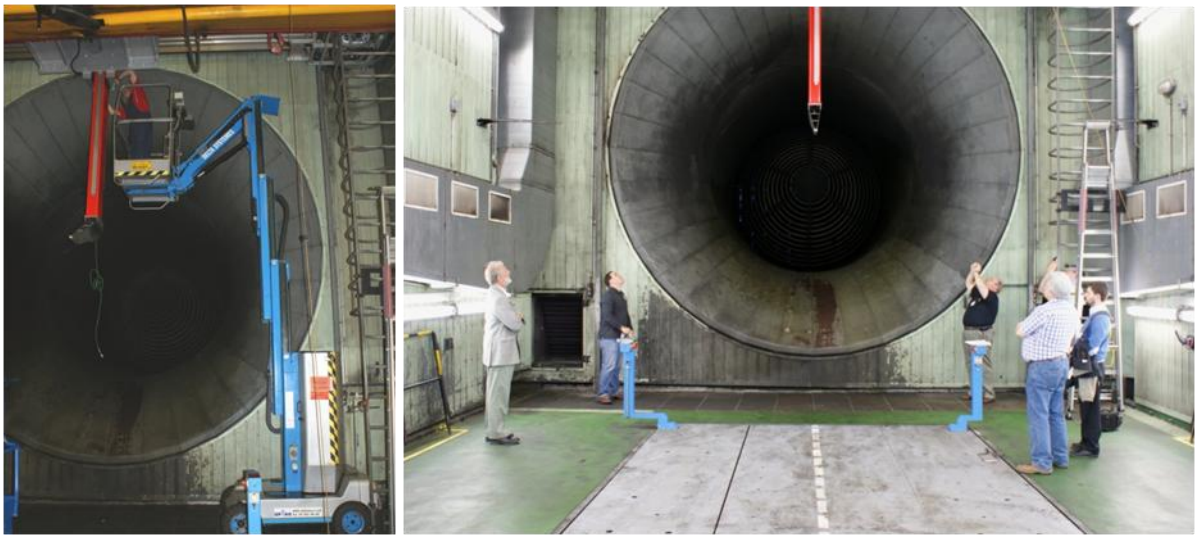

**Figure 81 Photograph of new 1-D traversable probe fitted into engine test bed at SR Technics, Zurich.**

There is considerable support to facilitate PM sampling during the numerous (>100) break in tests conducted per annum. There is permission at SR Technics for sampling to be conducted during data acquisition/trim balance testing, which significantly increases the available testing time at this facility. If an engine is tested in this regime, sampling at high power conditions is granted which enables sampling at high power for prolonged periods of time (circa 10 minutes).

It has also been highlighted that there is the potential of gaining longer testing windows by purchasing test time on SR Technics owned engines which could be fitted into natural gaps in the current testing schedules, but this would incur sizable fuel costs.

Engine data provided to FOCA usually include corrected thrust in ambient condition, measured thrust, RPM_N1, Ambient pressure, Pressure P3, Ambient humidity, EGT, Temperature T3, Ambient temperature, and fuel flow. Those are matched with PM and Gaseous measurements. The release of the data to third parties is done on a case to case basis, depending on commercial sensitivity. Engine serial numbers will not be provided.

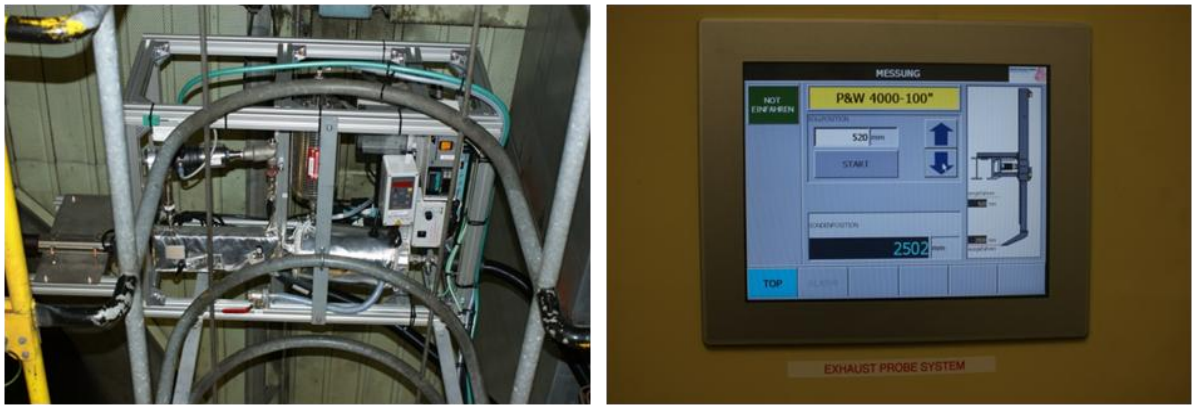


**Figure 82 (a&b) Photograph of primary dilution point of concept ARP sampling system fixed within test bad, and integration of test probe control into existing software at SR Technics, Zurich.**

SR Technics has demonstrated that testing at engine sign off and maintenance test facilities is feasible subject to a suitably designed probe and sampling system being fitted and integrated

into current operator control software (Figure 82b) so as not to impact on current testing schedules.

A mixed exhaust engine test has already been conducted demonstrating the probe and sampling system capability as is shown in Figure 83. The results of this test campaign have been presented elsewhere (DP 18 SAE E31 Meeting Ottawa, June 2011) and are not discussed further at this time.

**Figure 83 Photograph of sampling probe behind tested mixed flow engine at SR Technics, Zurich.**

As can be seen in Figure 83 with a test bed specific probe design utilised at SR Technics does not guarantee the sampling position to be within half a nozzle diameter of the exhaust, however, with further investment specific engine probe heads could be designed and installed to achieve a more representative exhaust sample and compliance with annex 16. This highlights a potential benefit of installing sampling probes on specific engine pylons rather than to the test bed infrastructure as future sampling probes would always be positioned close to the exit plane of the engine exhaust and would not have to be interchanged dependant on the engine entering a specific test bed.

Details of the engines currently serviced at the SR Technics facility, Zurich are detailed in Table 26.

**Table 26 Selected data for the engines available at SR Technics**

| Engine type | Diameter (inches) | Max. Thrust (lbf) | Application |
|---|---|---|---|
| **CFM56 -5B** | 68.3 | 22 000 – 33 000 | A319 / A320 / A321 |
| **CFM56 -5C** | 72.3 | 31 000 – 34 000 | A340 |
| **CFM56 -7B** | 61.0 | 19 500 – 27 300 | B737 |
| **PW4000-94** | 94.0 | 52 000 – 62 000 | A310 |
| **PW4168** | 100.0 | 68 600 | A330 |

### 8.9.4 Case study: Off-wing engine testing at GE Caledonian, Prestwick

Contact: Alan Kelly (MD)

It is appreciated that EASA as funders desire to maximise their opportunities whilst minimising expenditure. However, after due consideration it was deemed that simultaneous negotiation with GE Caledonian may be considered as improper or inappropriate to GE Nantgarw, as the two subsidiaries may feel that they are being put into a position of competitive tendering for what is a research program that is of no benefit to their operability. The result of which may be that all collaborative programs between the SAMPLE III consortium and GE could have been jeopardised. Hence negotiations with GE Caledonian have not been made at this time.

The following information for GE Caledonian is limited to a preliminary paper study.

The facility at Prestwick principally deals with the GEnx and CF6 engine types. The GEnx engine is a next generation derivative of the GE90 that incorporates a greater use of composites and twin annular premixing swirler (TAPS) technology to reduce the combustor temperature and deliver a 30% reduction in NOx. Total engine throughput at the facility is approximately 150 per year. The current single test cell is only used for the CF6 family engines, although a second test cell for the GEnx is under construction and will come online during 2011. Currently serviced and overhauled GEnx engines are shipped to SNECMA for break-in and performance testing.

Costs for the installation of a probe in the test cell at GE Caledonian are likely to be broadly similar to those at GE Nantgarw. Some differences in the cost of facility personnel for engineering and installation may become apparent with detailed negotiation, although these differences are likely to be small and will depend upon the appetite of the management for any sampling and measurement program. Costs of an experimental program at Prestwick are likely to be higher than a similar program at Nantgarw as it is located geographically further away from the majority of the SAMPLE III consortium partners.

Overall the cost on a per engine basis of emission testing at GE Caledonian is likely to be higher than the equivalent costs at GE Nantgarw simply because of the lower engine throughput at this facility.

## 8.10 Sampling probe

This assessment has been greatly complicated but equally made necessary by the absence of a suitable PM sampling probe to collect emissions from an engine in an off-wing facility. In the absence of a suitable probe, an objective inter-comparison of sampling systems cannot be made and it will be necessary to revisit this assessment as further details are identified.

The issue of the sampling probe is central to obtaining good and representative data. The only portable sampling probe within the SAMPLE III consortium is the MMU traversing probe. This system was originally designed for on-wing testing (hence has much additional weight), and whilst it is of a modular design and so can be stripped down to a light-weight version, an initial assessment indicates that this concept of a transportable probe is unsuitable for future engine testing at the considered test facilities discussed earlier.

For sampling PM from production pass-off engines at Rolls-Royce or from off-wing in-service engines at maintenance facilities a suitable probe would need to be developed. There are no current designs for this task. However, lessons and comparisons can be drawn from the work done at SR Technics.

For due consideration of this option, contact has been made with Theo Rindlisbacher of FOCA to gain insight into the associated costs and difficulties of this task. Initial upper cost estimates from FOCA suggested that €100k would be required for the design and construction of a single test bed specific sampling probe, with a further €100k for the installation and operation. However, more recent figures have been revised downwards: The cost of the vertical traverse probe including probe installation is now estimated at €77k, with a further €65k for the cost of on-site support, engineering, adaptations and sample line installation support up until the end of 2011. Hence FOCA estimate that the overall cost to install and run the PM sampling system at the SR Technics test cell to be €140k for the period up until the end of 2011 (however, this did not include the associated man power costs of project management and engineering donated by FOCA). However, verbal discussions with Rolls-Royce and GE Aero (Mark Johnson, Paul Madden, Will Dodds and Russ Arey) have indicated that due to the higher thrust levels encountered with large fan diameter engines (larger than tested at SR Technics), a probe of similar design to SR Technics would likely be at least double the cost in order to withstand the much greater force on the probe.

It has also been highlighted that there are IP issues associated with Rolls-Royce designing a probe for a GE facility and in addition, as Rolls-Royce are the lead partner of the SAMPLE III consortium, they could not carry the contractual risk of a consortium-owned probe located at a GE facility. Thus, GE would need to design and own the probe at a GE facility in order for a SAMPLE III consortium to conduct PM measurements.

To assess the feasibility and optimum characteristics of a sampling probe to acquire representative PM emission samples at engine maintenance facilities, the probe design criteria must be considered in more detail and the complexity would vastly increase.

Through communications with Theo Rindlisbacher of FOCA a number of design criteria have arisen:

- The probe can be used during break-in testing following an engine overhaul but would need to be retractable as its presence would not be allowed during engine performance testing.
- PM sampling may also be permissible during trim balance and data acquisition runs (if thorough comparative experiments show the probe has limited effect to measured engine parameters).
- At Zurich, Rolls Royce and GE Nantgarw, the floor area behind the engine must be kept clear or is unsuitable to mount a probe upon.
- A simple hinged probe sampling at a fixed position relative to the engine would sample at different relative locations for different engine types. Any asymmetry in PM emissions will be undeterminable.

From these criteria it is possible to begin to develop a decision tree as shown in Figure 8. Ideally cost elements and design challenges should be integrated into this tree, however the installation of a PM sampling probe at any one of the facilities must be considered as a

bespoke engineering project with its own individual and unforeseen difficulties and so may not be directly comparable with the installation of a probe at an alternative site.

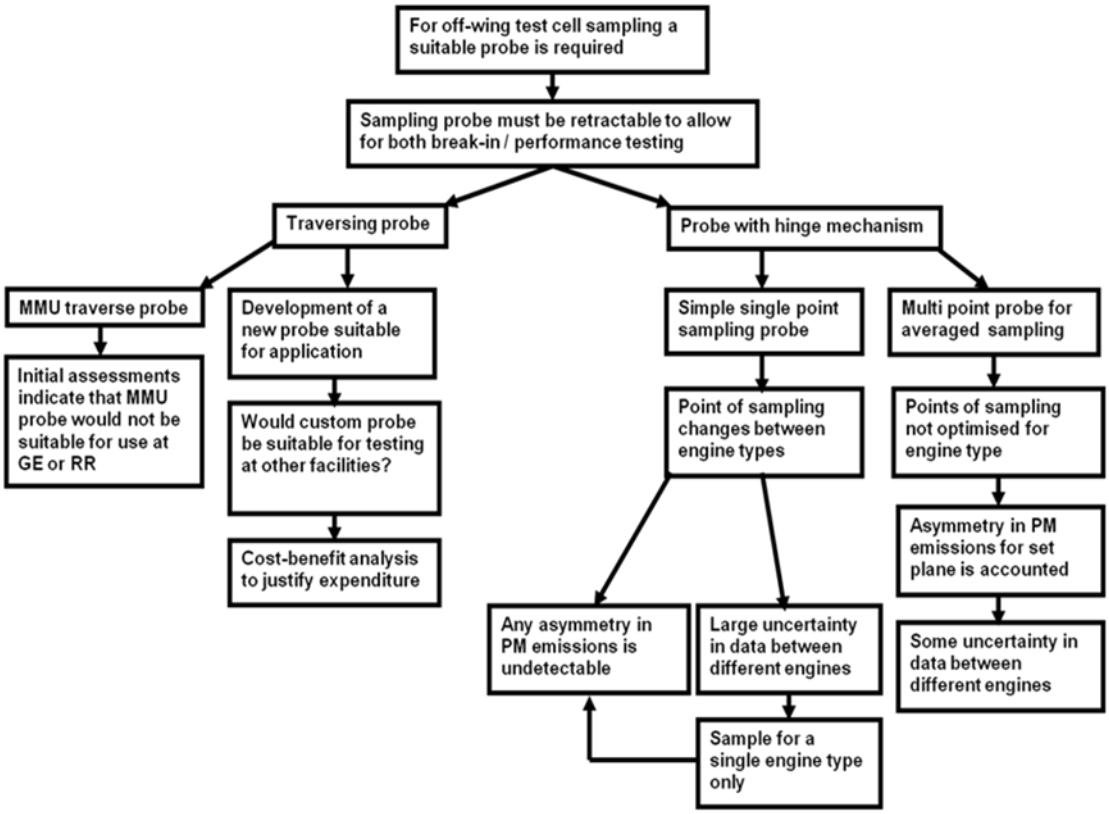


**Figure 84 Decision tree of possible probe designs**

A discussion of asymmetry in PM emissions in the exit plane of a gas turbine engine was given in the SAMPLE II report. Data in this report highlights the significant difference in the emissions that may occur across the exit plane. However, on a commercial in-service aircraft engine, any inherent asymmetric variations in the emissions should be less pronounced as the majority of engines are fitted with exhaust mixers.

Concerns of this nature were recently highlighted (SAE E31 Annual Meeting Ottawa, June 2011) by Pratt & Whitney and GE Aero who emphasised that reproducible, representative PM measurements could and should not be done during engine break in testing. This is due to the wearing/transient nature of the seal rub break in. For these reasons engine break in data is not suitable for generating representative non-volatile PM number and mass concentrations for specific engines but should be considered as a cost effective method of demonstrating functionality of proposed ARP compliant sampling systems.

## 8.11 Estimated costs

At this time, the development of a fully costed proposal is not possible since details of the PM sampling probe and details of the experimental configuration required by the funder have not been specified. Nevertheless, a table of cost estimates that is based upon best estimates from relevant sources has been included below. Figures given are for a single test campaign. Multiple test runs bring appreciable economies of scale.

**Table 27 Comparative cost of in-service engine emissions testing.**

| Cost Description | Off-wing non-certification testing at GE Nantgarw €k | Off-wing non-certification testing at Rolls Royce €k | Off-wing certification testing at Rolls Royce €k | Off-wing non-certification testing at SR Technics €k |
|---|---|---|---|---|
| **Probe design & construction** *Additional probe (j)* | 250 (c) (g) | 130 (b) (g) *12* | 0 | [ 77 ] (a) (h) |
| **Facility manpower & installation** | 130 (c) | 150 (b) | 0 | [ 65 ] (a) (h) |
| **Potential opportunity per year** | Up to 330 engines | Up to 150 engines (if large >110inch fan diameter) unmixed considered only) | Up to 2 engines | Up to 250 engines |
| **Fuel (if emission tests run concurrently)** | 0 | 0 | 0 | 0 |
| **Insurance** | Undetermined | 0 | 0 | 0 |
| **Single test period coordination (inc T&S)** | 6 | 6 | 15 | 30 |
| **Data analysis & reporting** | 2.4 | 2.4 | 2.4 | 2.4 |
| **Instrument Rental (i) (for one month inc administration)** | 85 | 70 | 70 | 78 |
| **PM ARP concept Sampling system hardware** | 34.8 | 0 (e) | 0 (e) | 0 |
| **Consumables** | 2.5 | 2.5 | 6.6(d) | 0 |
| **Engine time if purchased** | Undetermined | Undetermined | Undetermined | Determined (k) |
| **ARP PM Instrument Equipment if purchased – would replace rental cost (includes size measurement to ascertain lower size cut-off limit).** *Payback period = 6 tests* | 480 (f) | 480 (f) | 480 (f) | 480 (f) |

*Notes:* (a) Costs for SR Technics are exclusive of organisational (FOCA) manpower *(b) Initial probe estimate from Rolls-Royce for probe within tail-fairing, Facility manpower also includes project management cost (The addition of probes to multiple pylons at Rolls-Royce would enable engine PM testing to occur towards a daily basis); (c) Probe estimate from GE Aero for similar concept as at SR Technics; (d) one off cost for on-site calibration; (e) Rolls Royce have diluters, cyclones, heated line & controls available on-site; (f) 2010 instrument price list; (g) may be reduced with FOCA probe design collaboration;* (h) Costs from Theo Rindlisbacher shown in parenthesis indicate previous expenditure; (i) differences due to additional undiluted and/or primary diluted $CO_2$ analysers. It should also be noted that if a Smoke Number measurement is required, this capability already exists at Rolls Royce, other sites would need additional rental cost. *(k) Details of costs have been circulated to potential funding agencies.*

***Experimental running costs.*** The experimental running costs for in-service non-certification engine testing are broadly similar to those for certified engine testing. In both of these cases, differences in cost for consumable, test coordination, travel & subsistence and data reporting are generally small. Although a semi-permanent installation could potentially reduce logistics and manpower costs per test.

***Capital / Infrastructure costs.*** Off-wing in-service non-certification emissions testing at an engine maintenance facility would require capital investment for the design and installation of a PM suitable probe. At SR Technics the cost of probe design and construction was €77k and the cost of installation was a further €65k [FOCA] (not including engineering & project management time donated by FOCA). However, based upon discussions with Rolls-Royce and GE Aero it is unlikely that these costs can be realised for a probe designed for the significantly larger engines within the facilities discussed herein.

The installation of a PM sampling probe at any one of the facilities must be considered as a bespoke engineering project that does not lend itself to detailed costing as there are many unforeseen difficulties. Furthermore, the capital investment required for the design and installation of a suitable PM sampling probe is unrecognisable as an auditable asset as its cost far exceeds the value of its component parts. However, the relatively large cost of this probe may be reduced by design collaboration with FOCA and this one-off cost must be considered in terms of the multiple measurement opportunities that may be realised, albeit on a limited number of engine types.

***Equipment costs.*** There are a number of useful equipment items that are not inherent to the consortium including a suitable VPR, suitable CNC and LII or S-MAAP. Some of these items have previously been borrowed or rented, however, it is unlikely that long term loans will be possible. For a sustained measurement campaign in a semi permanent facility looking at the emissions from a number of engine types, rental costs may become prohibitive and a strong business case for the purchase of these items could to be made. This is a problem common to all methods of in-service engine testing.

An inventory list of equipment that is potentially available within the SAMPLE III consortium is given in Appendix A. Specific costs for equipment on this inventory can only be determined as detailed methodologies are developed so that an estimate of equipment usage costs based upon standard depreciations can be included. On a semi-permanent installation where equipment may be required to stay on site for some time, these costs may be appreciable as the equipment is not available to support other contracts.

***Fuel costs.*** Fuel usage for in-service non-certification engine testing is likely to be similar to those for certified engine testing. The cost of this fuel is often a sizeable proportion of the budget in any engine testing program. In consequence, the coordination of engine emission tests that run in conjunction with standard commercial engine tests is desirable. For conjunctive engine testing opportunities there would be no fuel cost, whilst for paid engine testing opportunities fuel costs are likely to be similar.

## 8.12 Conclusions of Task 3c

1. In principle, there are a considerable number of opportunities for in-service non-certification engine testing across Europe.
2. In general, individual maintenance facilities largely specialise in a small number of specific engine types. To obtain data that is representative of the in-service fleet will require measurements at multiple sites.
3. Access to all of the engine types within these facilities could require an appreciable amount of negotiation between the consortium, the maintenance facility and the engine owner. However, these negotiations have already been conducted at SR Technics and R-R Derby.
4. Off-wing in-service non-certification engine testing at engine maintenance or production pass-off facilities are feasible but would require a significant cost in terms of probe installation (with the exception of SR Technics Zurich).
5. Of the two GE engine maintenance facilities considered, GE Aircraft Engine Services, Nantgarw, would appear to offer a greater number of measurement opportunities in comparison to GE Caledonian for a similar cost over a specific time frame.
6. If permission was granted it is expected that testing could commence at either the GE Nantgarw or R-R Deby sites on a timescale of approximately 6 to 9 months (assuming the probe has already been designed and manufactured in this period).
7. There is already a fully commissioned sampling probe and line at SR Technics (Zurich). Thus this offers the immediate feasibility of conducting SAE E31 Committee approved concept demonstration measurements (instrument inter-comparison, VPR assessment, SAE E31 Committee approved sampling line functionality etc.) on a limited number of engine types.
8. To install a probe at either GE Nantgarw or R-R Derby would require a capital investment for the design and installation of a suitable probe. The relatively large cost of this probe (estimated at €250k) must be considered in terms of the multiple measurement opportunities, on a limited number of engine types.
9. At R-R Derby a concept PM sampling probe design built into the tail fairing of the prod pylon is partially recoverable in terms of cost by economies of scale, since the probe design can then be replicated on other prod pylons at reduced cost and measurements on multiple engine types can be realised.
10. The consortium feel that there would be some extra complication in conducting a conceptual test by the SAMPLE III consortium at SR Technics (Zurich) due to the logistics associated with the import and export of test kit to a facility located outside of the EU.
11. The absence of an identifiable transportable sampling probe for off-wing engine testing at each site. Hence individual probe designs would be required at each site, this is an important consideration. Defined and representative sampling is fundamental to good measurement practice. Without good sampling, measurements of non-volatile PM number and mass loading may be subject to considerable uncertainty.

# 9. Task 4: Uncertainty Analysis of Errors in Aircraft Engine Non-volatile Particle Emission Measurements

This Section of the report is adapted from a National Physical Laboratory report (ISSN 1754-2928) prepared for the SAMPLE III consortium, by Paul Quincey of the Analytical Science Department at the National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW who acted as a sub-contractor of the SAMPLE III consortium.

## 9.1 Introduction, Scope and Approach

### 9.1.1 Background

The aim of the document is to evaluate uncertainties (errors) in specific aircraft engine particle emission measurements, linking them to the calibrations and checks that are required or that may be needed in future SAE PM Measurement ARP procedures. As the relevant working draft ARP is not due to be available until June 2012, it is not possible to provide a definitive evaluation of it at this stage (October 2011). The aim of this section is to evaluate the procedures as they are currently anticipated, and to highlight critical aspects of the measurements, so that when the ARP is finalised (a ballot-ready non-volatile PM mass and number ARP is currently expected by February 2013) it will contain measurement procedures with well-justified uncertainties that have been minimised through consideration of their key components.

The main areas to be tightened up or determined by experiment are

For number concentration:

- Definitions of the required low size cut-off; lowering the value below 23 nm will also affect many of the factors below;
- Variability of volatile particle content after VPRs;
- Concentrations of $CO_2$ in the dilution air;
- Losses at cyclones, diluters, and other components not as well modelled as pieces of tubing;
- Losses in the tubing parts of the sampling line, though recent results show good agreement with theory.

For mass concentration:

- Comparability of mass concentration measurements made by Laser Induced Incandescence (LII), Multi Angle Absorption Photometer (MAAP) and Photoacoustic spectroscopy (PAS) – this will be clarified by an ongoing study being carried out by the US EPA;
- Calibration procedures for LII, MAAP and PAS;
- Typical drifts for LII, MAAP and PAS;
- Impact of volatile PM and volatile coated PM on PAS measurements (LII & MAAP have been shown experimentally to be insensitive to pure volatile particles)
- Mass-based losses at cyclones, diluters, and other components not as well modelled as pieces of tubing.

### 9.1.2 Scope

Before analysing the uncertainties of a measurement, it is important to clarify what we are trying to measure. The sampling system under consideration is that designed and built by the consortium which is based on the SAE E31 Committee approved sampling system as discussed earlier in Section 5 of this report. A flow diagram of the whole sampling system is presented earlier in Figure 45. It is divided functionally into the three sections, namely: Collection, Transfer, and Measurement. In practice the characteristics of the Collection section will be much more specific to the engine type and measurement facility than the other two sections, and it is thus considered in a different way to the other two standardised sections.

The system under detailed consideration is therefore limited to the Transfer and Measurement sections of the sampling system, starting from the gas/PM sampling split. This will be referred to below as "the system".

The purpose of the system is to determine both a number concentration parameter and a mass concentration parameter for non-volatile particles within a certain size range at the gas/PM sampling split. The size range and "non-volatile" particles are defined below. Both number concentration and mass concentration measurements will be described.

#### *9.1.2.1 Number concentration in the Transfer and Measurement sections*

For number concentration, the system dilutes the air stream before the number concentration is measured at the Condensation Particle Counter (CPC), to reduce new particle nucleation, and to ensure concentrations are within the counting range of the CPC. If volatile particles and particle losses within the system are neglected, the measured number concentration at the CPC simply needs to be combined with a measured dilution factor to produce the concentration at the gas/PM sampling split. The consortium built measurement suites and non-volatile PM sampling line were shown and demonstrated in Section 6.2.2 and are shown schematically in Figure 53. They allow total dilution factors of around 1000, which would potentially be confirmed utilising the measurement of $CO_2$. The existence of significant size-dependent particle losses, along with the need to remove volatile particles, are the major complicating factors in the measurement.

The desired size range is effectively defined by the lowest particle size chosen to be measured. The upper limit (set by the cyclone in the PM measurement system at around 1 μm) has little effect on the measurement, as the vast majority of particles are smaller than this.

At the SAE E-31 meeting in Ottawa in June 2011 it was decided initially to set the low size limit to 23 nm. Although many non-volatile emitted particles are expected to be smaller than this, the size was chosen as a compromise between including all relevant particles and reducing measurement uncertainty by reducing the effect of volatile particles, and of particle losses in the system, which will be larger for smaller particles. The value of 23 nm is also the same as that chosen by the UNECE Particle Measurement Programme for vehicle emissions, leading to practical advantages in both analysis of the method and availability of equipment. However, it should be highlighted that this value may be changed to a lower value in future.

Volatile particles are defined as those that are removed after exposure to a temperature of 350ºC.

The measured quantity can therefore be initially defined as:

*Number concentration (in $cm^{-3}$) of non-volatile particles in the nominal size range 23 nm to 1 µm at the gas/PM sampling split. The air volume is to be corrected to Standard Temperature and Pressure (273.2K and 101.33 kPa).*

Typical number concentrations at the gas/PM sampling split during a test range from around 5 x $10^3$ to 1 x $10^8$ $cm^{-3}$, with concentrations typically in the range $10^6$ to $10^7$ $cm^{-3}$. These numbers will be considered below. It is important to note that the definitions of volatility, size range and indeed number concentration are in practice defined operationally. In this type of situation, the role of the uncertainty analysis is to evaluate possible variations of the measurement result when implementing the procedures, rather than to evaluate uncertainties with respect to absolute (SI) definitions, as this is not appropriate.

The inlet concentrations are diluted within the system, in part to keep concentrations within the range in which standard CPCs count individual particles without excessive coincidence errors. With a total dilution factor of 1000, the concentration range to be measured by the CPC for this measurement is around $10^3$ to $10^4$ $cm^{-3}$.

The low size cut-off is fixed by the low-size detection curve of the CPC. In the PMP, the CPC performance characteristic is defined as detection efficiency of 50 ±12% at 23 nm and >90% at 41 nm, though the particle material to be used for this test is not defined. This definition will be used here.

The particle concentration measurement has the basic measurement Equation (9):

$$C_{split} = C_{CPC} \, x \, D_{gas} \, x \, F_{lossTM} \qquad (9)$$

Where $C_{CPC}$ is the number concentration measured by the CPC, $D_{gas}$ is the dilution factor in the system as measured by gas concentration, and $F_{lossTM}$ is a correction for particle losses in the Transfer and Measurement sections.

At the SAE E-31 meeting in Ottawa in June 2011 it was decided that no correction would be made for particle losses, in other words setting $F_{lossTM}$ to 1, the intention being that losses would be standardized between facilities by design criteria. This was partly in consideration of the fact that particle losses will be size dependent, and in general the actual size distribution will be unknown. In practice this size dependence is relatively small for particles above 23 nm, so the decision can be seen as anticipating a move to a lower particle size limit in future. However, variations between facilities, especially the inlets to such components as the cyclone and diluters, will be a major component of the total uncertainty, so this factor is treated separately in the analysis below.

In effect, the definition of the measured quantity should be redefined as:

*Number concentration (in $cm^{-3}$) of non-volatile particles in the nominal size range 23 nm –1 µm at the gas/PM sampling split as reduced by particle losses in the standard sampling system. The air volume is to be corrected to Standard Temperature and Pressure (273.2K and 101.33 kPa).*

This definition makes explicit the fact that the measured quantity is operationally defined through the standard method, and not an objective measure of actual particle number concentrations at a specified point. Although, in general, objective measures should be preferred, this is one of many instances where a pragmatic approach is needed for regulatory purposes.

The contribution of volatile particles not removed by the VPR does not appear in the measurement equation, but is treated as part of the CPC measurement for the purposes of uncertainty.

#### *9.1.2.2 Number concentration in the Collection section*

The effect of the Collection section on the final result for number concentration is treated in a different way, because it is possible neither to standardize the components, nor to measure their effect on number concentrations directly. For this section the losses are calculated theoretically (based on both diffusive and thermophoretic losses), and a correction applied. As above, in principle knowledge of the particle size distribution is needed, but the effect of ignoring the size distribution is relatively small when the low size limit is set to 23 nm.

The full measured quantity is therefore Equation (9):

*Number concentration (in $cm^{-3}$) of non-volatile particles in the nominal size range 23 nm –1 µm at the inlet probe as reduced by particle losses in the standard sampling system after the gas/PM sampling split. The air volume is to be corrected to Standard Temperature and Pressure (273.2K and 101.33 kPa).*

$$C_{emission} = C_{CPC} \times D_{gas} \times F_{lossC} \times F_{lossTM} \qquad (10)$$

Where, $C_{emission}$ is the concentration at the inlet probe and $F_{lossC}$ is the correction for particle losses in the collection section.

#### *9.1.2.3 Mass concentration*

The mass concentration measurement is in many ways similar to the number concentration measurement, though with different instrument issues (i.e. calibrating the LII, MAAP, or PAS), a lower dilution factor, no conditioning (as there is no Volatile Particle Remover), and different losses in the Collection and Transfer sections, because the effect of these losses on mass is heavily weighted towards larger particles.
In the case of mass concentration, the low size limit is not critical (and will be dependent on the low size sensitivity of the particular mass measurement instrument used) because

although there will be large numbers of particles at the smaller sizes, their contribution to the total mass is minor.

The measured quantity can be given as:

*Mass concentration (in µg/m$^3$) of non-volatile particles in the nominal size range 5 nm –1 µm (in the case of an Artium 300 LII mass analyser) at the inlet probe as reduced by particle losses in the standard sampling system after the gas/PM sampling split. The air volume is to be corrected to Standard Temperature and Pressure (273.2K and 101.33 kPa).*

with the measurement Equation (11):

$$M_{emission} = M_{inst} \, x \, D_{gasM} \, x \; F_{lossCM} \, x \; F_{lossTMM} \qquad (11)$$

Where $M_{emission}$ is the mass concentration at the inlet probe, $M_{inst}$ is the mass concentration measured by the mass measurement system, $D_{gasM}$ is the dilution factor in the system as measured by gas concentration, $F_{lossCM}$ is a correction for particle losses in the Collection section, and $F_{lossTMM}$ is a correction for particle losses in the Transfer and Measurement sections.

### 9.1.3 Related Activities in Other Areas

#### *9.1.3.1 Particle Measurement Programme (Vehicles)*

The UNECE Particle Measurement Programme (PMP) is aimed at developing robust measurement procedures for vehicle particle emissions. An analogous study into errors and uncertainties in particle number concentration measurements was carried out in the PMP in 2007.

This study concluded:

*A provisional rough estimate of the uncertainty for particle concentration measurements, based on the figures and assumptions used here, is 15%. This uncertainty figure corresponds to a level of around 95% confidence. It should be emphasised that it is not possible to be fully rigorous or definitive, because there will be variations in how the methods are carried out in practice, and some of the factors are not well characterised. Nevertheless, this should be a realistic approximate figure.*

*The major factors are the calibration of the particle number counter (PNC), an area where it is acknowledged that international standardisation is required, and the reproducibility of the Particle Conditioning and Measuring System (PCMS).*

*The error calculation applies when total dilution factors of 150 are used. In all cases, high dilution factors make the measurements more prone to errors, because the actual particle dilution factor is more difficult to determine. When a dilution factor around 600 is used, for example with a Gasoline Direct Injection (GDI) engine, additional care would be required to ensure that statistical variations, and the effects of leakage and "noise", were addressed*

*during the dilution factor measurement. The calibration procedures recommend suitable measures and similar uncertainties could still be obtained.*
*It is important that significant factors such as reproducibility and test source stability are properly quantified and controlled within the procedures. Consideration should be given to retrospective correction of data using subsequent calibration results.*

*Although more than 99% of volatile particles are removed by the Volatile Particle Remover (VPR), the presence of a 1% fraction of the volatile particles emitted by the vehicle could have a significant influence on results, but this effect is not investigated in detail here.*

The figure of 15% was found to agree well with later comparison results.

The approach of this study closely follows the PMP work. However, several major differences between this work and PMP work need to be emphasised. Firstly, the PMP study was limited to the part of the measurement system described here as the Conditioning and Measurement section, because losses analogous to those in the Collection and Transfer sections were considered to be relatively small. Secondly, the combination of dilution and particle losses in this section were directly measured at three different sizes (30 nm, 50 nm and 100 nm) as Particle Concentration Reduction Factors (PCRFs), so that there was no need to evaluate such losses theoretically. And thirdly, procedures on how to calibrate the CPC, measure PCRFs etc were available in advanced draft form, so that many tolerance criteria were clear, and it was also clear where tolerance criteria were needed but absent.

#### *9.1.3.2 Ambient air standardisation in Europe*

A second related activity comes from measurements of particle number concentration in ambient air. Particle number concentration does not feature in Air Quality legislation, but it may be a candidate in the future. In anticipation of this, the European standardisation body CEN has set up a Working Group to standardise the sampling and measurement of particle number concentration such that measurements across Europe would be comparable (CEN TC 264 WG 32).

Although the Technical Specification document is at quite an early stage, there are important areas of overlap that have been addressed, notably in the treatment of sampling losses.

Resolution 22 (Brussels, September 2010) states that *the Technical Specification shall state a range of particle losses permitted in the sampling line caused by diffusion to the walls. This shall be given as a percentage losses of particles (for example 10-25%) at a specified particle size (for example 7 nm), that shall be determined from the parameters for flow rates, tube diameters etc by formulae or graphs to be included in the Technical Specification.*

The sample line losses in this case are simpler than for aircraft engine emissions, as only diffusion losses need to be considered (thermophoretic losses being negligible), and sample lines are relatively short. On the other hand, the lower size limit for ambient measurements is provisionally set at 7 nm, making sampling losses relatively more significant.

#### *9.1.3.3 Standardisation of CPC Calibration within ISO*

The introduction of vehicle legislation for particle number has given impetus to efforts to standardise a method to calibrate CPCs, so that results will be more robust and more comparable. This is being done within ISO TC 24 SC4 WG 12, who have written a near final draft standard that will become ISO 27891.

### 9.1.4 Approach

There are several different approaches to uncertainty analysis and this report is based on that of the ISO Guide to the Expression of Uncertainty in Measurement (GUM 1995). In this approach, you:

(1) define an equation that is used to produce the result from various input measurements and parameters;

(2) identify the various operational factors that influence the result, based on a practical understanding of the measurement process;

(3) quantify the uncertainty in each of these factors;

(4) evaluate the effect of each of these uncertainties on the result by how each factor features in the equation; and

(5) combine the effects of all the factors, typically by adding them in quadrature (ie taking the square root of the sum of their squares).

Within this document, the equation in (1) is defined in Section 9.1.2 above; the factors (2) are identified in Section 9.2; the uncertainty in each factor (3) and its effect on the final result (4) are given by the "Limits" and "Effect on result" columns respectively in Section 9.3; and the combination of effects (5) is given in Section 9.5.

## 9.2 Factors affecting the measurements

### 9.2.1 Number concentration

The tables below are meant to help focus on the factors that affect the measurement set out in Section 9.2. They are not an exhaustive list, but should include the most important factors in each case and help fill calculating Equation (10).

#### *9.2.1.1 Factors affecting the number concentration measured by a CPC ($C_{CPC}$)*

The major factors that affect the $C_{cpc}$ are presented below in Table 28.

**Table 28 Factors affecting the number concentration measured by a CPC**

| Factor | Symbol |
|---|---|
| CPC number concentration calibration accuracy<br>- the accuracy is relative to other CPCs used for the same purpose<br>- the calibration is done at a particle size well above the low size cut off (typically 50 – 100 nm)<br>- the accuracy will vary with the number concentration due to factors such as coincidence (at concentrations above ~5,000 $cm^{-3}$ ) and background noise (at low concentrations).<br>- The accuracy depends on the particle material used for CPC calibration, especially at low size | $C_1$ |
| CPC number concentration drift since calibration, eg due to change in flow rate. | $C_2$ |
| Presence of volatile particles | $C_3$ |
| Comparability of the CPC low size cut-offs | $C_4$ |
| Corrections to STP | $C_5$ |

#### *9.2.1.2 Factors affecting accuracy of gaseous dilution ratio ($D_{gas}$)*

The determination of $D_{gas}$ is assumed to be based on the ratio of $CO_2$ concentrations measured at the gas/PM sampling split (by the gas analysis system) with expected values of ~2% by volume in the raw exhaust, which would result in a concentration in the PM measurement system, downstream of all diluters, of ~20 ppm (i.e. 0.1% of original value at 1000:1 dilution). There have been recent SAE E31 Committee discussions about using a calibrated dilution factor, with the gas dilution measurement taking the form of a check on this, but this is not considered in the analysis and care should be taken at high dilution ratios (>150:1) as uncertainties will increase significantly. These two $CO_2$ measurements will necessarily be made by independent instruments. In principle these are relatively

straightforward measurements, but uncertainties can still be significant. The major factors are outlined in Table 29.

**Table 29 Factors affecting determination of gaseous dilution ratio measured by a $CO_2$ analyser**

| Factor | Symbol |
|---|---|
| Accuracy of the high concentration $CO_2$ measurement, including span calibration, zero error, sampling line leaks / losses, instrument drift since calibration. | $D_1$ |
| Accuracy of the low concentration $CO_2$ measurement, including span calibration, zero error, sampling line leaks / losses, instrument drift since calibration. | $D_2$ |
| Presence of $CO_2$ in the dilution air | $D_3$ |

### *9.2.1.3 Factors affecting the correction of particle losses in the Collection Section ($F_{lossC}$)*

The factors affecting the correction of particle losses in the Collection Section are given in Table 30.

**Table 30 Factors affecting correction for particle losses in the collection section.**

| Factor | Symbol |
|---|---|
| Errors in the estimated diffusive losses within the specified inlet probe. | $F_{C1}$ |
| Errors in the estimated thermophoretic losses within the specified inlet probe | $F_{C2}$ |

These factors will depend on the actual size distribution of the particles being emitted from the engine.

### 9.2.1.4 Factors affecting correction of particle losses in the Transfer and Measurement sections ($F_{lossTM}$)

The factors affecting correction for particle losses in the Transfer and Measurement sections are given in Table 31.

**Table 31 Factors affecting correction for particle losses in the Transfer and Measurement sections**

| Factor | Symbol |
|---|---|
| Variations in diffusive losses between different implementations of the transfer and measurement sampling systems. | $F_{TM1}$ |
| Variations in thermophoretic losses between different implementations of the transfer and measurement sampling systems. | $F_{TM2}$ |
| Variations in other losses found experimentally, such as within cyclones and diluters | $F_{TM3}$ |

All of these factors will depend on the actual size distribution of the particles being emitted from the engine. The factors are shown schematically on the fishbone diagram below in Figure 85.

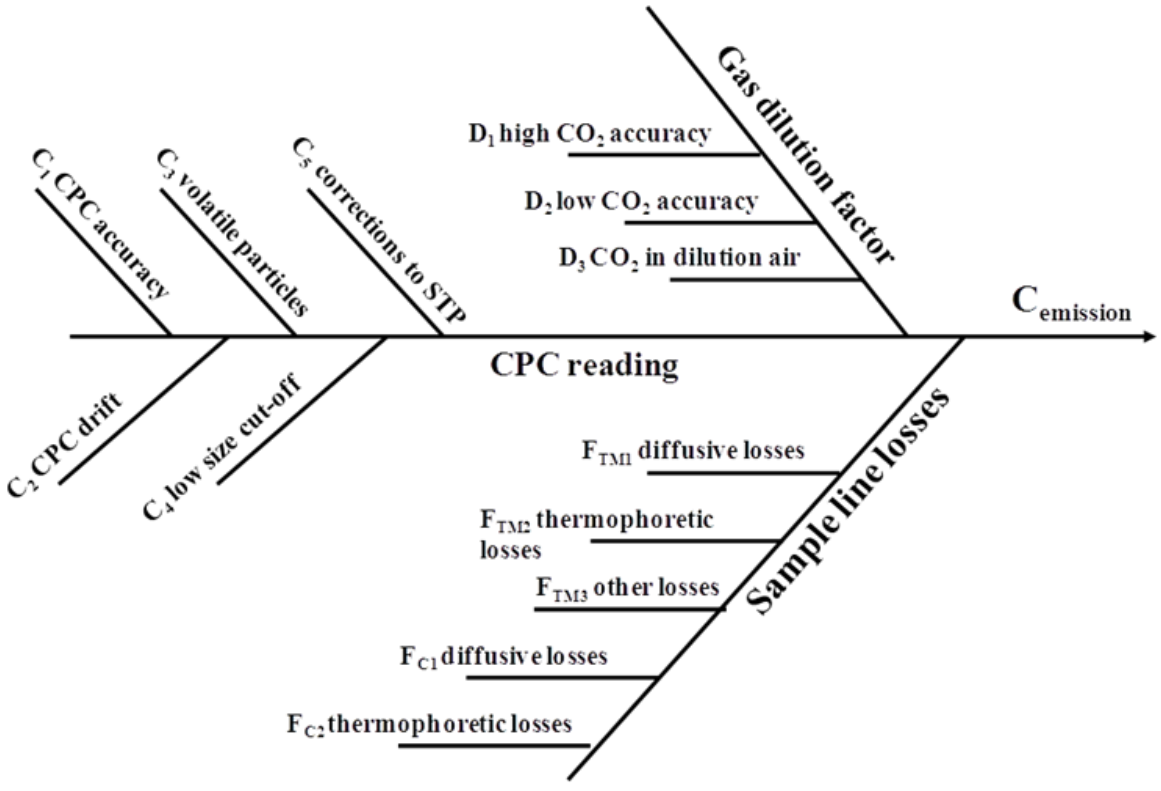


**Figure 85 Fishbone diagram for particle number concentration measurements**

### 9.2.2 Mass Concentration

The tables below are meant to help focus on the factors that affect the measurement set out in Section 9.1, similar to those in Section 9.2.1. In this case the measurement equation is taken to be as was presented in Equation (11):

#### *9.2.2.1 Factors affecting Mass measuring Instruments ($M_{inst}$)*

The factors affecting the mass measuring instruments are outlined below in Table 32.

**Table 32 Factors affecting Mass Measuring Instruments**

| Factor | Symbol |
|---|---|
| LII or MAAP or PAS mass concentration calibration accuracy | $M_1$ |
| LII or MAAP or PAS drift since calibration | $M_2$ |
| Presence of volatile particles | $M_3$ |
| Corrections to STP | $M_4$ |

#### *9.2.2.2 Factors affecting dilution ratio by gaseous measurement ($D_{gasM}$)*

The factors affecting $D_{gasM}$ are presented below in Table 33.

**Table 33 Factors affecting accuracy of dilution ratio calculation by gaseous $CO_2$ measurement**

| Factor | Symbol |
|---|---|
| Accuracy of the high concentration $CO_2$ measurement, including span calibration, zero error, sampling line leaks / losses, instrument drift since calibration. | $D_{M1}$ |
| Accuracy of the low concentration $CO_2$ measurement, including span calibration, zero error, sampling line leaks / losses, instrument drift since calibration. | $D_{M2}$ |
| Presence of $CO_2$ in the dilution air | $D_{M3}$ |

#### *9.2.2.3 Factors affecting losses associated with mass in the Collection section ($F_{lossCMass}$)*

The factors affecting $F_{lossCMass}$ are presented below in Table 34.

**Table 34 Factors affecting mass losses in section A ($F_{lossCMass}$)**

| Factor | Symbol |
|---|---|
| Errors in the estimated diffusive losses | $F_{CMass1}$ |
| Errors in the estimated thermophoretic losses | $F_{CMass2}$ |

### 9.2.2.4 Factors affecting mass loss in the Transfer and Measurement sections ($F_{lossTMMass}$)

The factors affecting $F_{lossTMMass}$ are presented below in Table 35

**Table 35 Factors affecting mass losses in the Transfer and Measurement sections ($F_{lossTMMass}$)**

| Factor | Symbol |
|---|---|
| Variations in diffusive losses between different implementations of the transfer and measurement sampling systems. | $F_{TMMass1}$ |
| Variations in thermophoretic losses between different implementations of the transfer and measurement sampling systems. | $F_{TMMass2}$ |
| Variations in other losses found experimentally, such as within cyclones and diluters | $F_{TMMass3}$ |

The factors are shown schematically on the fishbone diagram below Figure 86.

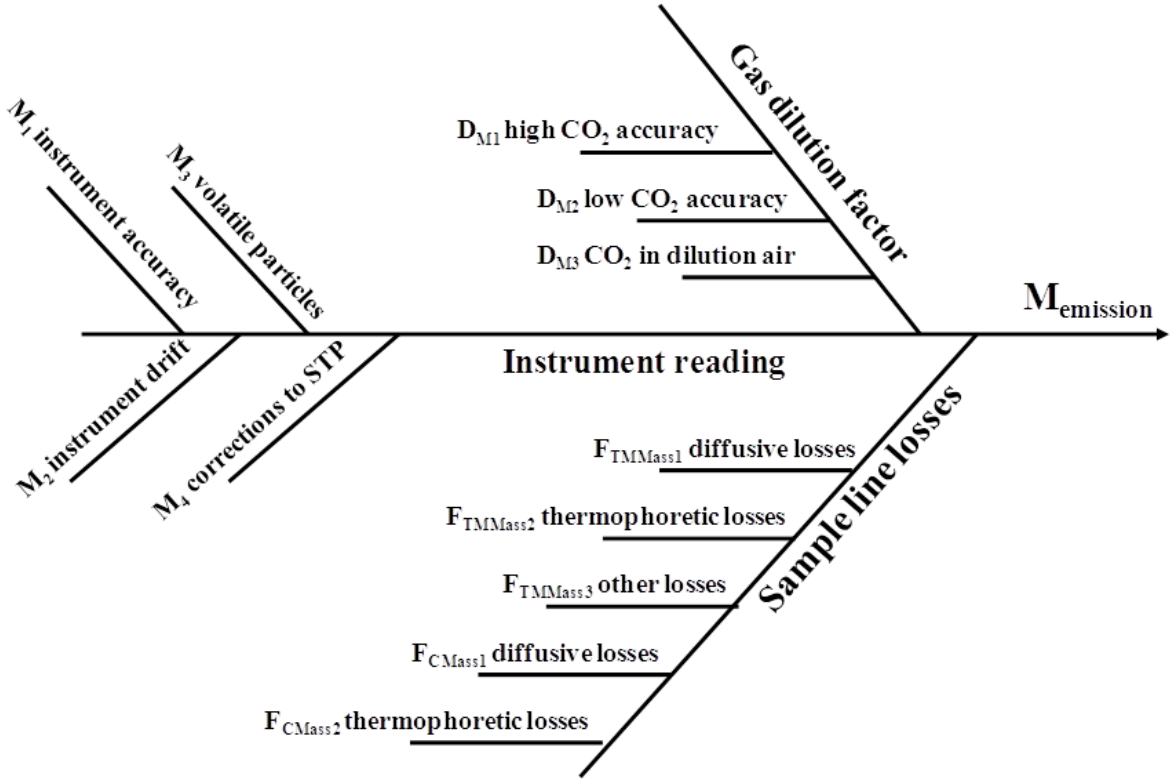


**Figure 86 Fishbone diagram for particle mass concentration measurements**

## 9.3 Quantification of the factors

### 9.3.1 Number concentration

As stated earlier, as the system has not been finalised it is not possible to accurately quantify all of the associated losses, however, those that can be given with some confidence are given in the following sections.

#### *9.3.1.1 Quantification of Factors affecting number concentration measured with CPC ($C_{CPC}$)*

**Table 36 Quantification of factors affecting number concentration measured with a CPC**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **CPC accuracy** | $C_1$ | Calibration procedure | 10% | 10% | The details of the calibration procedure are important. The figure is based on PMP requirements. |
| **CPC drift** | $C_2$ | Knowledge of typical drift between calibrations | ~5% in 6 months (in NPL's experience) | ~5% | Drift between calibrations should be monitored |
| **Volatile particles** | $C_3$ | Allowed efficiency of volatile particle remover | Depends on number of volatile particles in typical sample | <3% | If the lower size limit is reduced below 23nm, the factor will depend strongly on the VPR technology |
| **Low size cut-off** | $C_4$ | Procedure and criteria for low size cut-off determination | TBD | | This will depend on the concentration of particles around the cut-off size |
| **Corrections to STP** | $C_5$ | Maximum outlet temperature and pressure | | Expected ~2% | Outlet temperature and pressure should be checked |

### 9.3.1.2 Quantification of Factors affecting dilution ratio measurement by gaseous $CO_2$ measurement ($D_{gas}$)

**Table 37 Quantification of factors affecting dilution ratio measurement by gaseous $CO_2$ measurement**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **High $CO_2$ accuracy** | $D_1$ | Calibration procedure and checks | | Expected ~ 2% | |
| **Low $CO_2$ accuracy** | $D_2$ | Calibration procedure and checks | | Expected ~ 3% | |
| **$CO_2$ in dilution air** | $D_3$ | Measurement procedure and checks | | Negligible | With the low concentration $CO_2$ at 0.1% there are no special requirements for the dilution air. |

### 9.3.1.3 Quantification of Factors affecting Loss in the Collection Section ($F_{LOSSC}$)

**Table 38 Quantification of Factors affecting Loss in the Collection Section ($F_{LOSSC}$)**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **Diffusive losses** | $F_{C1}$ | Actual sampling probe parameters | | Until PM sampling system is fully approved by SAE E31 this cannot be assessed therefore effects on build sample line presented | An estimate of uncertainty for these losses is combined with those in the other sections in 9.3.1.4. |
| **Thermophoretic losses** | $F_{C2}$ | Actual sampling probe parameters | | Until PM sampling system is fully approved by SAE E31 this cannot be assessed therefore effects on build sample line presented | An estimate of uncertainty for these losses is combined with those in the other sections in 9.3.1.4. |

#### *9.3.1.4 Quantification of Factors affecting Loss in the Transfer and Measurement Sections ($F_{LOSSTM}$)*

**Table 39 Quantification of Factors affecting Loss in the Transfer and Measurement Sections ($F_{LOSSTM}$)**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **Diffusive losses** | $F_{TM1}$ | Sampling design tolerances | | ~10% | Uncertainties in diffusive and thermophoretic corrections for the whole sample line are estimated from the results in Section 9.4. |
| **Thermophoretic losses** | $F_{TM2}$ | Sampling design tolerances | | | This |
| **Other losses** | $F_{TM3}$ | Specification of parts | Diluter max loss specification 10% | ~5% | Estimate of uncertainty when a correction is made for parts such as diluters. |

### 9.3.2 Mass concentration

#### *9.3.2.1 Quantification of Factors affecting measurement of mass with mass instruments ($M_{inst}$)*

**Table 40 Quantification of Factors affecting measurement of mass with mass instruments ($M_{inst}$)**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **LII or MAAP or PAS accuracy** | $M_1$ | Calibration procedure | | Results will be available soon from US EPA | The details of the calibration procedure are important. |
| **LII or MAAP or PAS drift** | $M_2$ | Knowledge of typical drift between calibrations | Not yet established | | Drift between calibrations should be monitored |
| **Volatile particles** | $M_3$ | Allowed efficiency of volatile particle remover | Depends on mass of volatile particles and volatile coatings in typical sample | Expected to be neglible/low for LII and MAAP; not known for PAS | This will depend on the sensitivity of the chosen technique to volatile material. |
| **Corrections to STP** | $M_4$ | Maximum outlet temperature and pressure | | Expected ~2% | Outlet temperature and pressure should be checked |

### 9.3.2.2 Quantification of factors affecting dilution ratio calculation for mass measurement by gaseous $CO_2$ measurement ($D_{gasM}$)

**Table 41 Factors affecting dilution ratio calculation for mass measurement by gaseous $CO_2$ measurement ($D_{gasM}$)**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **High $CO_2$ accuracy** | $D_{M1}$ | Calibration procedure and checks | | Expected ~ 2% | |
| **Low $CO_2$ accuracy** | $D_{M2}$ | Calibration procedure and checks | | Expected ~ 3% | |
| **$CO_2$ in dilution air** | $D_{M3}$ | Measurement procedure and checks | | negligible | With the low concentration $CO_2$ at 0.1% there are no special requirements for the dilution air. |

### 9.3.2.3 Quantification of Factors affecting mass losses in the Collection Section ($F_{LOSSCMass}$)

**Table 42 Quantification of Factors affecting mass losses in the Collection Section ($F_{LOSSCMass}$)**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **Diffusive losses** | $F_{CMass1}$ | Actual sampling probe parameters | | | An estimate of uncertainty for these losses is combined with those in the other sections in 9.3.2.4. |
| **Thermophoretic losses** | $F_{CMass2}$ | Actual sampling probe parameters | | | An estimate of uncertainty for these losses is combined with those in the other sections in 9.3.2.4. |

### 9.3.2.4 Quantification of Factors affecting mass loss in the Transfer and Measurement Sections ($F_{LOSSTMMass}$)

**Table 43 Quantification of Factors affecting mass loss in the transfer and measurement sections ($F_{LOSSTMMass}$)**

| Factor | Symbol | Constraint | Limits | Effect on result | Comment |
|---|---|---|---|---|---|
| **Diffusive losses** | $F_{TMMass1}$ | Sampling design tolerances | | ~10% | Uncertainties in diffusive and thermophoretic corrections for the whole sample line are estimated from the results in Section 9.4. |
| **Thermophoretic losses** | $F_{TMMass2}$ | Sampling design tolerances | | | See above. |
| **Other losses** | $F_{TMMass3}$ | Specification of parts | | Not known | Mass losses within components have not been well established. Will be minimal compared to number performance specifications. |

## 9.4 Preliminary approximation of Transmission Efficiency through Proposed SAE accepted Non-volatile PM Sampling Line & Annex 16 Collection Section

Theoretical physical modelling for PM transport losses have been performed using the UTRC particle transport model. The effects of line temperature along with differing ICAO Annex 16 setups have been studied to show the effect of system parameters on over all particle transmission and thus overall uncertainty.

### 9.4.1 Transmission Efficiency through Consortium Built non-volatile PM Sampling Line

As was demonstrated in Section 6.3.2, the majority of losses in the sampling line appear to occur in the 25m grounded PTFE line for this reason the approximation of this section has been modelled to include diffusion losses with thermophoretic losses added for different perceived future configurations and analyser sample lines. The output of the model is presented below in Figure 87.

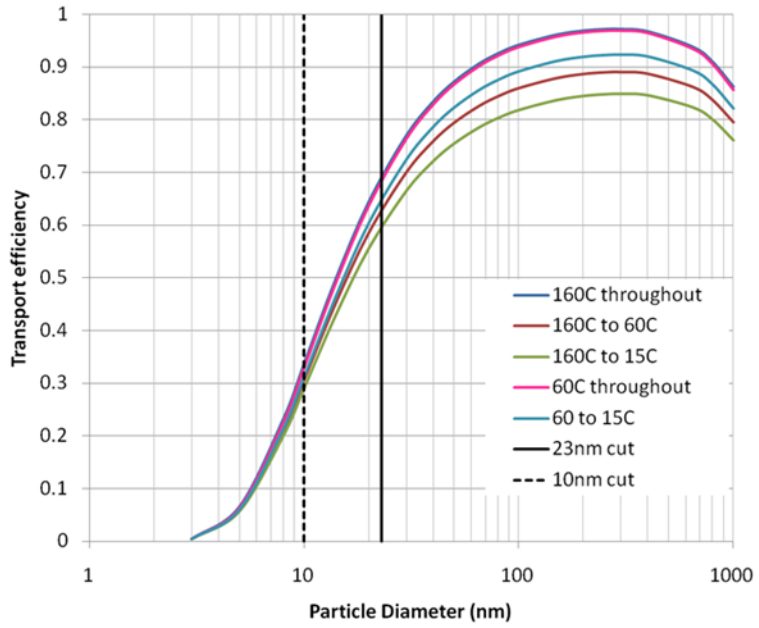


**Figure 87 Transport efficiency model for 25m Line at various temperature gradients**

As can be seen the lower cut point chosen has a massive effect on the transmission efficiency witnessed with only 30% of 10nm particles passing through the line compared with 70% of 23nm particles penetrating if a uniform 160°C line is used. It is also highlighted that it is not desirable to change the sample line temperature along its length as additional thermophoretic losses are witnessed across the entire size distribution which adds to the overall uncertainty associated with line loss in this section.

### 9.4.2 Transmission Efficiency through ICAO Annex 16 PM Collection Section

The variation in the quantity of non-volatile particle loss in the Collection section of the sampling system between different existing designs of ICAO Annex 16 compliant systems could generate large measurement uncertainties for both non-volatile mass and number measurement. In addition the variation of non-volatile particle size distribution in the gas turbine exhaust could also significantly impact the number measurement uncertainty.

To assess the impact of possible Collection section variations, particle line loss modelling was performed on two types of Collection systems with a comparison of different standardised Transfer system lengths included. These systems were loosely based on a range of existing compliant manufacturer ICAO Annex 16 systems. The sampling system parameters inserted into the model are described below in Table 44.

**Table 44 Specification of modelled sample system parameters**

| Case | Parameter | Collection system | | Transfer System (standardised) | |
|---|---|---|---|---|---|
| | | 1PTS | 2PTS | 17m | 25m |
| Case 1 | Length (m) | 2 | 6 | 17 | 25 |
| | ID (mm) | 1 | 1 | 7.85 | 7.85 |
| | Velocity (m/s) | 35.4 | 21.7 | 10.3 | 10.9 |
| | Residence time (s) | 0.06 | 0.28 | 1.6 | 2.3 |
| Case 2 | Length (m) | 3 | 0 | 0 | 25 |
| | ID (mm) | 23 | - | - | 7.85 |
| | Velocity (m/s) | 1.0 | - | - | 10.9 |
| | Residence time (s) | 3 | - | - | 2.3 |

The results of the model are shown in Figure 88 along with labels to help indicate where possible non-volatile number low size cut-offs could occur at 23 & 10nm. It can be observed that there is a large difference (20-30%) in particle penetrations between the two cases, which varies with particle diameter.

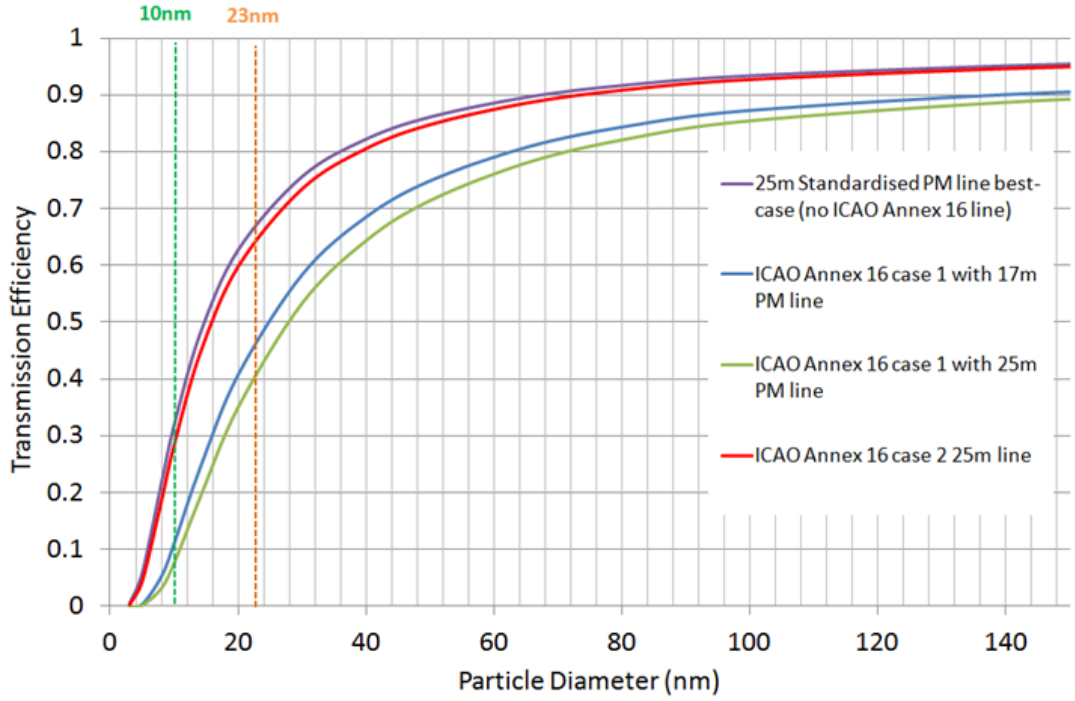


**Figure 88 Comparison of particle losses for possible different Collection (1PTS & 2PTS) designs with an additional standardised PM sampling system**

To attempt to understand the variation divergence between the two cases and the impact on number and mass measurement, Figure 89 shows an example particle size distribution in both number and volume modes measured from a modern large full-scale gas turbine exhaust downstream of PMP-type VPR (SAMPLE II) together with the % variation in particle loss witnessed in Figure 88. It is observed that at particle diameters < 60nm the variation flattens out and can be approximated to a constant offset of ~10%.

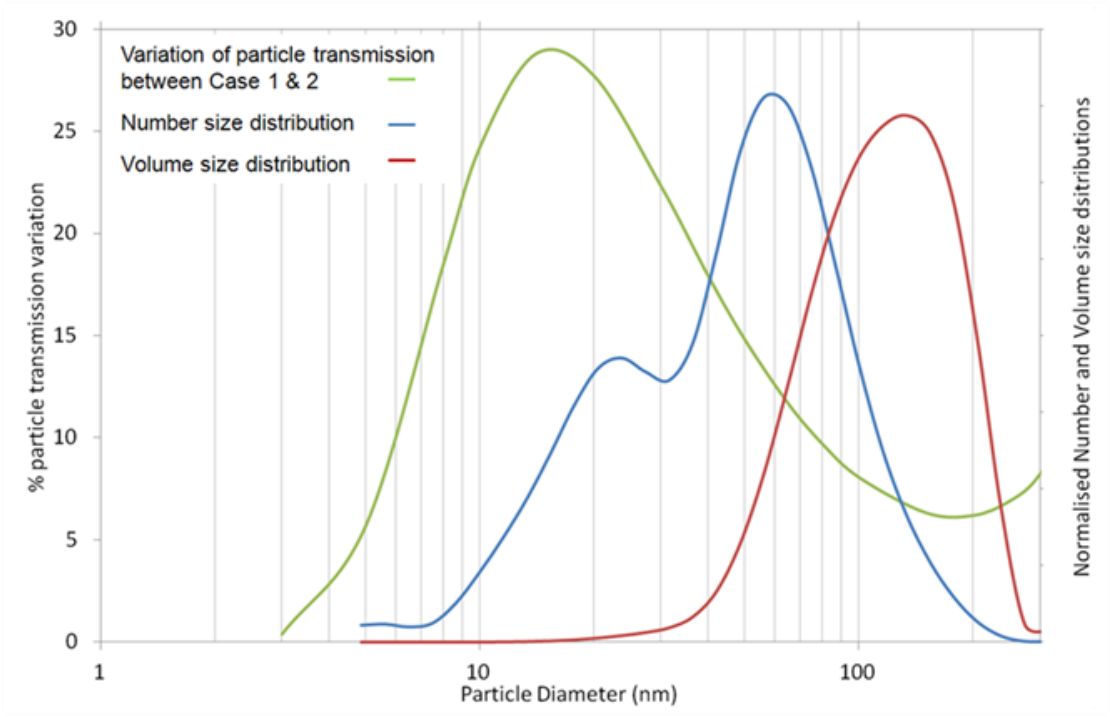


**Figure 89 Effect of particle transmission on number and volume size distribution between to ICAO Annex 16 cases**

For this specific engine type/condition exhaust size distribution the cumulative 95% volume/mass concentration occurs at 65nm, thus a theoretical average performance loss correction factor (for a specific sampling Collection system) can be applied to the non-volatile mass data with a high confidence and minimal uncertainty impact. However, if volume size distributions occur at smaller median diameters then the confidence will slightly decrease affecting an increase in uncertainty. This increase in uncertainty can only be determined with the knowledge of expected volume size distributions across the measured engine combustor types.

For non-volatile number concentration measurement the associated uncertainties are higher due to the sharp increase in variation from 10 to 30%, peaking at 17nm before sharply decreasing towards zero at <5nm particle sizes. This means that any small difference in number size distribution will significantly (>20%) increase the measurement uncertainty of non-volatile number concentration.

The question is raised as to whether it is more beneficial for regulators to have better inter comparison between different engine manufacturers or a better measurement uncertainty for non- volatile PM number, as to achieve better comparability a small low size cut-off should be adopted (5nm) (which would include the total non-volatile particle combustion distribution) . Conversely a larger low cut-off size (23nm) should be adopted if a lower measurement uncertainty is of greatest concern (due to the reduction in area between the Case curves in Figure 89). The PMP approach to this issue is that the measurement system defines the metric thus it is of utmost importance to achieve good reproducibility of results from laboratory to laboratory and the measurement system is then used to set the metric.

This specific engine type/condition exhaust size distribution has a cumulative 90% non-volatile number concentration occurring at 17nm, and the cumulative 95% non-volatile

number concentration occurs at 13nm. The cumulative number concentration at the steady variation level (>60nm) is only 37%, thus trying to correct the particle loss using an average loss correction factor is inadvisable due to the extremely high (>60%) measurement uncertainties that this would produce.

A range of measured size distributions from a variation of modern aviation gas turbine combustor types should be performed in order to determine what the range is expected and thus the uncertainties associated for both mass and number attributed to the sampling variation within the Collection section can be established.
Theoretical Collection performance transmission efficiencies at specified particle sizes 15, 30, 50 and 100nm for both cases are shown in Figure 90. If these performance efficiencies are modelled and/or experimentally established for all existing Annex 16 systems across all manufacturers, the data range could be used to determine the measurement uncertainty associated with the variation in ICAO compliant systems.

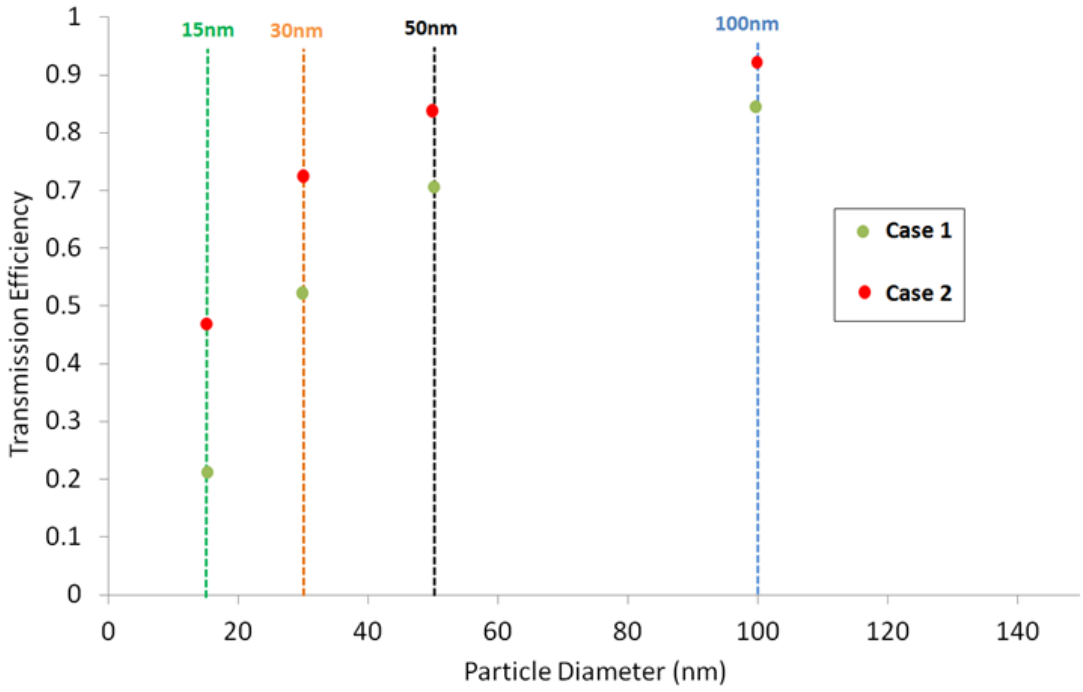


**Figure 90 Theoretically modelled particle transmissions at specific particle sizes**

### 9.4.3 Impact of Thermophoretic losses in transport of Sample from ICAO Annex 16 Collection Section to SAE E31 Committee Approved PM Sampling Line

An attempt of modelling the entire system from probe tip to analyser inlet was then conducted and is presented in Figure 91. However, the authors concede that the uncertainty of this second model is much higher and probably significantly under predicts losses as a number of assumptions have been made including a lack of diffusion losses in the sample probe and first 7m line section (as this will be variable and specific to individual engine sample probe configurations as prescribed in Annex 16). Other assumptions made are that there are no thermophoretic losses in the primary diluter. This assumption could however be corrected for in the future by performing a PMP type PCRF correction for the diluter running at the specific operating temperatures that will be prescribed by the future non-volatile PM ARP.

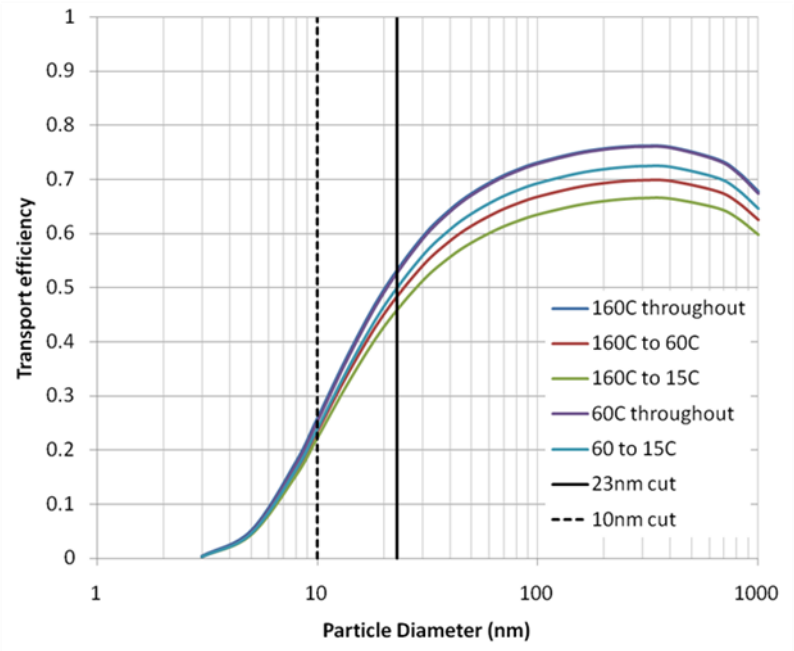


**Figure 91 Transport efficiency model for entire sample line at various temperature gradients**

As can be seen even though the model is known to be under predicting losses there are sizable losses particularly to small particles with at a maximum only 20% of 10nm particles penetrating the sampling system. This increases to over 50% if a 23nm limit is chosen.

## 9.5 Perceived Uncertainty Knowledge Gaps

In order to 'fill in' the uncertainty gaps to determine the overall uncertainty, the main areas to be tightened up or determined by experiment are presented below for non-volatile number measurement in Table 45:

**Table 45 Perceived gaps in knowledge for non-volatile number measurement**

| | Uncertainty gap description | Requirements to address gaps |
|---|---|---|
| 1 | Definitions of the required low size cut-off; lowering the value below 23 nm will also affect many of the factors below | Perform non-volatile size distribution measurements on a large number of different types of modern gas turbine combustor designs across engine operating powers to determine range of expected possible non-volatile size distributions. |
| 2 | Variability of volatile particle content after VPR | Perform size distribution measurements up and downstream of VPR and perform long term (due to high dilution ratios) OC/EC filter measurements on real gas turbine exhaust |
| 3 | Particle losses through cyclones, diluters, and other components not well modelled as pieces of tubing | Define/determine cyclone performance specifications.<br>Perform PMP PCRF check measurements on specific components to ensure they meet defined performance specifications.<br>Perform experimental vs theoretical solid PM penetration measurements of multiple types of existing ICAO compliant probe/rake systems |
| 4 | Losses in the tubing parts of the sampling line | Replication of SAMPLE III SC01 results should be performed to ensure concurrence |

Similarly there are gaps in the knowledge associated with the measurement of non-volatile PM mass and these are given in below in Table 46.

**Table 46 Perceived gaps in knowledge for non-volatile mass measurement**

| | Uncertainty gap description | Requirements to address gaps |
|---|---|---|
| 1 | Comparability of mass concentration measurements made by LII, MAAP and PAS | Conclude US EPA study.<br>Perform intercomparison measurements on gas turbine exhausts across a range of volatile/non-volatile mass ratios |
| 2 | Calibration procedures for LII, MAAP and PAS | Define calibration specification |
| 3 | Typical drifts for LII, MAAP and PAS | Perform long term (months) drift check measurements on specific components to ensure they meet defined performance |
| 4 | Impact of volatile PM and volatile coated PM on PAS measurements (LII & MAAP have been shown experimentally to be insensitive to pure volatile particles) | Perform instrument sensitivity volatile and volatile coating impact experiments using a volatile particle evaporation generator with a solid carbon particle generator to produce relevant volatile mass concentrations that could be encountered in an aviation gas turbine exhaust.<br>Perform measurements on gas tubine exhaust across a range of volatile mass concentrations |
| 5 | Mass-based losses at cyclones, diluters, and other components not well modelled as pieces of tubing. | Define/determine cyclone performance specifications<br>Perform PMP PCRF check measurements on specific components to ensure they meet defined performance specifications.<br>Perform experimental vs theoretical solid PM penetration measurements of multiple types of existing ICAO compliant probe/rake systems |

In addition after the standardised system is fully defined as a working draft ARP, inter-comparison measurements should be performed with independent standardised sampling systems with full instrument suites utilising a common 1PTS/2PTS system on multiple full-size gas turbine exhausts. The experiment should exercise the sampling and measurement systems across the full range of possible operating parameters and expected non-volatile and volatile PM ratios and concentrations. The repeatability between the two independent systems for non-volatile mass and number should fall within the defined overall uncertainty. If it does not, additional work will be required to address the extra uncertainty with repeated experiments where necessary.

## 9.6 Conclusions of Task 4

1. Although it is premature (due to the delays in SAE E31 Committee to define a working draft ARP) to form full quantitative conclusions about the overall uncertainties of these measurements, the methodology for doing so is clearly set out, and the areas that need further evaluation have been identified.
2. The provisional combined uncertainty for the non-volatile number concentration measurement (assuming 23nm cut-off), from the figures included in the preceding tables, and is approximately 17%.
3. There are a number of undetermined specifications (described in Table 45) of which the largest and most significant is expected to be the uncertainty associated with the currently unspecified low size cut-off with the lower the cut-off adopted the higher the associated uncertainty.
4. The largest components of uncertainty for non-volatile number in terms of system hardware, derive from the calibration of the CPC and the lack of correction for sample line losses particularly through the non standardised Annex 16 collection section (1PTS & 2PTS).
5. For non-volatile number measurement if dilution ratios >150:1 are utilised the provisional uncertainty could increase to 19% if the PMP protocol for acceptable diluent background is followed (<0.5 #/$cm^3$).
6. If dilution ratios are not measured online for 4PTSn then the provisional uncertainty will increase to 20% for 150:1 dilution ratios and will further increase to 22% if higher dilution ratios are utilised (with the PMP protocol).
7. The corresponding combined uncertainty figure for the non-volatile mass concentration measurement is around 10%. However, there are a number of undetermined components (described in Table 46) such as the comparability, volatile sensitivity and calibration of the mass instruments, which are expected to increase the overall figure significantly.

# 10. Conclusions

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

1. As expected the PMP approved commercially available VPR (Dekati DEED, AVL APC400) as well as the bespoke consortium designed conform to PMP protocol in terms of laboratory based testing.
2. The Grimm ESS VPR did not meet all of the specifications set out by the PMP, it is thought that the reason for this is the lack of evaporation tube and lower temperatures utilised by the unit.
3. It was found that PMP VPR do not 'remove' all of the volatile PM but shrink over 99% of the volatile PM to a size below the 23nm cut off selected by PMP. As discussed earlier this could lead to large uncertainties particularly if the volatile to non-volatile PM number ratio is high.
4. Catalytic Stripper technology appeared to completely remove tetracontane and lubrication oil in the form of pure volatile PM and volatile coated carbon particles and would pass PMP VPR performance specifications although it does not conform to PMP design specification.
5. Data suggests that PMP type diluters could be 'slightly' modified to potentially reduce the attainable lower size cut-off by increasing the primary dilution temperature along with the evaporation tube temperature.
6. It was witnessed during numerous combustor and full scale engine tests that volatile particles appear to exist throughout the measureable PM size range, and are not only present in the primary nucleation mode peak as current scientific understanding would suggest.
7. Online non-volatile PM mass measuring instruments (MAAP & LII) are insensitive to PMP approach tetracontane volatiles at loadings representative of modern large scale gas turbine engines (as witnessed in SAMPLE II Rolls-Royce full-scale engine test).
8. It is thought that a reduction in uncertainty could be gained by not using a PMP type PCRF which includes the preset dilution ratio, by including an online gaseous measurement to calculate the actual dilution ratio witnessed during testing which has been shown to be sensitive to fluctuation in sample line pressure.
9. A sampling system meeting current specifications laid out by the SAE E31 Committee has been designed and built and performed suitably for use in testing a full scale APU engine.
10. Performance specifications for specific components of future standardised sampling systems have been proposed by the consortium but have not been currently ratified by the SAE E31 Committee at present.
11. Further work will be required to define a specification suitable for volatile particle removal efficiency for use in aero type exhausts as it is felt the current PMP approach may not provide low enough uncertainties.
12. Sheffield Universities Artouste APU is a suitable vehicle for the repeat testing required to validate a sampling system.
13. The use of the proposed sampling system utilising an eductor type primary diluter has been successfully demonstrated on a low thrust full scale APU engine.
14. Losses in terms of PM number and size have been measured along the consortium designed a built (SAE E31 Committee) proposed PM sample line length, with good agreement being observed when compared against theoretical thermophoretic and diffusion models.

15. Measured penetration data provides evidence that the transport efficiency of the consortium built (SAE E31 Committee approved) proposed sampling system can be approximated to theoretical calculations for the long 25m PTFE heated line and that as long as the sampling system is kept within 1.5m downstream of the cyclone outlet the additional particle losses are negligible.
16. The provision of the two simplifications of the sampling interface discussed in 7.2 will enable provision of non-volatile PM measurements on any future large full-scale certification-type engine test in R-R Europe assuming that an SAE E31 sampling concept standardised system is available
17. Throughout 2011 there has been and will still continue to be, good communication between consortium members and instrument rental manufacturers. If future funding and EASA still require full-scale modern engine testing, R-R are committed to provide PM testing opportunities and support, and the consortium will do everything reasonably possible to try and get PM sampling and measurement instruments to a certification- type engine test when one next occurs at R-R Derby, Dahlewitz or INTA.
18. In principle, there are a considerable number of opportunities for in-service non-certification engine testing across Europe.
19. In general, individual maintenance facilities largely specialise in a small number of specific engine types. To obtain data that is representative of the in-service fleet will require measurements at multiple sites.
20. Access to all of the engine types within these facilities could require an appreciable amount of negotiation between the consortium, the maintenance facility and the engine owner. However, these negotiations have already been conducted at SR Technics and R-R Derby.
21. Off-wing in-service non-certification engine testing at engine maintenance or production pass-off facilities are feasible but would require a significant cost in terms of probe installation (with the exception of SR Technics Zurich).
22. Of the two GE engine maintenance facilities considered, GE Aircraft Engine Services, Nantgarw, would appear to offer a greater number of measurement opportunities in comparison to GE Caledonian for a similar cost over a specific time frame.
23. If permission was granted it is expected that testing could commence at either the GE Nantgarw or R-R Deby sites on a timescale of approximately 6 to 9 months (assuming the probe has already been designed and manufactured in this period).
24. There is already a fully commissioned sampling probe and line at SR Technics (Zurich). Thus this offers the immediate feasibility of conducting SAE E31 Committee approved concept demonstration measurements (instrument inter-comparison, VPR assessment, SAE E31 Committee approved sampling line functionality etc.) on a limited number of engine types.
25. To install a probe at either GE Nantgarw or R-R Derby would require a capital investment for the design and installation of a suitable probe. The relatively large cost of this probe (estimated at €250k) must be considered in terms of the multiple measurement opportunities, on a limited number of engine types.
26. At R-R Derby a concept PM sampling probe design built into the tail fairing of the prod pylon is partially recoverable in terms of cost by economies of scale, since the probe design can then be replicated on other prod pylons at reduced cost and measurements on multiple engine types can be realised.
27. The consortium feel that there would be some extra complication in conducting a conceptual test by the SAMPLE III consortium at SR Technics (Zurich) due to the

logistics associated with the import and export of test kit to a facility located outside of the EU.

28. The absence of an identifiable transportable sampling probe for off-wing engine testing at each site. Hence individual probe designs would be required at each site, this is an important consideration. Defined and representative sampling is fundamental to good measurement practice. Without good sampling, measurements of non-volatile PM number and mass loading may be subject to considerable uncertainty.
29. Although it is premature (due to the delays in SAE E31 Committe to define a working draft ARP) to form full quantitative conclusions about the overall uncertainties of these measurements, the methodology for doing so is clearly set out, and the areas that need further evaluation have been identified.
30. The provisional combined uncertainty for the non-volatile number concentration measurement (assuming 23nm cut-off), from the figures included in the preceding tables, and is approximately 17%.
31. There are a number of undetermined specifications (described in Table 45) of which the largest and most significant is expected to be the uncertainty associated with the currently unspecified low size cut-off with the lower the cut-off adopted the higher the associated uncertainty with transmission losses.
32. The largest components of uncertainty for non-volatile number in terms of system hardware, derive from the calibration of the CPC and the lack of correction for sample line losses particularly through the non standardised Annex 16 collection section (1PTS & 2PTS).
33. For non-volatile number measurement if dilution ratios >150:1 are utilised the provisional uncertainty could increase to 19% if the PMP protocol for acceptable diluent background is followed (<0.5 #/cm$^3$).
34. If dilution ratios are not measured online for 4PTSn then the provisional uncertainty will increase to 20% for 150:1 dilution ratios and will further increase to 22% if higher dilution ratios are utilised (with the PMP protocol).
35. The corresponding combined uncertainty figure for the non-volatile mass concentration measurement is around 10%. However, there are a number of undetermined components (described in Table 46) such as the comparability, volatile sensitivity and calibration of the mass instruments, which are expected to increase the overall figure significantly.

## 11. References


Stenitzer, M. (2003). Nano particle formation in the exhaust of internal combustion engines, Diplom-Ingenieurs, Technischen UniversitätWien, Fakultät für

Volatile Particle Remover Calibration and Validation Procedures , Report to the Department of Transport, AEA Energy & Environment ED47382004/VPR

Giechaskiel et al. (2009). SAE 2009-01-1115

Giechaskiel et al. (2009b). AST 43:1164–1173

Giechaskiel et al. (2010). MST 045102

Wang et al. (2010). JAS 41: 306-318

Sevcenco et al. (2010) ASME GT2010-23415,Glasgow

UNECE Addendum 82: Regulation No. 83, E/ECE/324/Rev.1/Add.82/Rev.4 – E/ECE/TRANS/505/Rev.1/Add.82/Rev.4

NPL Report AS 17: Particle Measurement Programme – Analysis of Errors, Richard Gilham and Paul Quincey, November 2007

GUM (1995) ISO/IEC Guide 98-3:2008 Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement

BGI website – "http://www.bgiusa.com/cyc/cyclone_facts.htm ", Jan. 2011

L.C. Kenny et al. "Characterization and Modeling of a family of Cyclone Aerosol Preseperators," J. Aerosol Sci. 24(4), pp. 677-688, 1997

R. Gussman -- BGI Tech Report. "Evaluation of a Sharp Cut Cyclone for PM1 Sampling", Jan. 2000

# Appendices

## A. Equipment matrix

The instrumentation deployed on an experimental measurement campaign is dependent upon the specific objectives, the availability of equipment, the availability of manpower and the overall budget. The following table gives an inventory list of equipment that is potentially available within the SAMPLE III Consortium.
The consortium does not own all of the required instrumentation for the currently proposed SAE E-31 sampling methodology. The table therefore also includes equipment items considered to be important but that must currently be loaned or rented.
The relative importance has been scaled for the measurement of non-volatile particles for the current E-31 ARP development. However, further prioritisation may become necessary in a budget or space constrained program.

**Table a. Summary of the instrumentation that is potentially available within the SAMPLE III consortium. (* indicates that the technique involves off-line analysis and that samples were captured during the trials for subsequent quantification).**

| Equipment | Acronym | Measurements | Importance | Equipment owner/operator |
|---|---|---|---|---|
| Richard Oliver Smoke Meter | SN | Smoke Number | M | CU |
| Aerosol Mass Spectrometer | AMS | Volatile component | L | UoM |
| Differential Mobility Spectrometer | DMS | Size and number | M | CU |
| Multi Angle Absorption Photometer | MAAP | Mass | M | DLR |
| Super Multi Angle Absorption Photometer | S-MAAP | Mass | H | Not available require manufacture |
| Laser Induced Incandescence | LII | Size and number | H | LOAN / RENTAL |
| Gravimetry* | GRAV | Mass | M | MMU |
| Optical Particle Counter | OPC | Number | M | DLR / UoM |
| Particle Soot Absorption Photometer | PSAP | Mass | L | DLR |
| Condensation Particle Counter | CPC | Number | H | UoM / LOAN / RENTAL |
| Scanning mobility particle sizer | SMPS | Size and number | L | UoM / ONERA |

| | | | | |
|---|---|---|---|---|
| Thermo Gravimetric Analysis* | TGA | Volatile and non-volatile mass | H | NPL subcontract |
| Scanning Electron Microscopy* | SEM | Size | M | MMU / ONERA |
| Faraday Cup Electrometer | FEC | | M | ONERA |
| Raman spectrometry | RS | Carbon composition / chemistry | L | MMU |
| Transmission Electron Microscopy | TEM | Size / carbon composition | L | ONERA |
| Flame ionisation detector | FID | Unburned hydrocarbons | H | UoS / CU |
| Fourier transform infrared | FTIR | Unburned hydrocarbons, some speciation info | L | LOAN / RENTAL |
| Carbon dioxide | CO2 (%) | Gaseous measurement | H | RR / UoS / CU |
| Carbon dioxide | CO2 (5000ppm) | Gaseous measurement | H | RR / UoS / CU |
| Carbon dioxide | CO2 (1000ppm) | Gaseous measurement | H | DLR |
| Carbon monoxide | CO | Gaseous measurement | H | RR/ UoS /CU |
| Suphur dioxide | SO2 | Gaseous measurement | L | RR / UoS / CU |
| Oxides of nitrogen | NOX | Gaseous measurement | H | RR / UoS / CU |
| On-wing traverse sampling rake | TR | Sample collection | | MMU |
| Mobile gas analysis trailer | MGA | | | RR / UoS |
| Volatile particle remover | VPR | Removal of volatile PM | H | LOAN / RENTAL |
| | | | | |

## B. Stakeholder analysis

The purpose of the following stakeholder analysis tables is to indicate the possible roles and responsibilities that Sample III consortium partners would take in any in-service non-certification engine testing. Clarification and conformation would be required from the project coordinator.

**Stakeholder Analysis: Off-wing testing at GE aircraft engine services, Nantgarw**

| Stakeholder | Stake in the project | Impact | What does the Project expect the Stakeholder to provide? | Perceived attitudes and/or risks | Stakeholder Management Strategy | Responsibility |
|---|---|---|---|---|---|---|
| GE aircraft engine services | Owner of maintenance facility<br>Operators of test cell | High | Use of test cell facility,<br>Cost of fuel,<br>Supporting data,<br>Determine procedures, | Technically oriented project<br>What is purpose of data?<br>Concern about increased workload / safety / delays | Update meeting with project leader as required,<br>Risk assessment package | Project partner / partial sponsor |
| Carriers / leasing companies | Owners of engines | High | Permission to record PM engine emission data,<br>Provide supporting data | Technically oriented project<br>What is purpose of data?<br>Where will data go?<br>Will data be commercially sensitive? | Update meeting with project leader as required,<br>Put NDA in place,<br>Anonomise data | Project partner / partial sponsor |
| EASA | Funding body, | High | Funding to support the project | Does it achieve objectives?<br>Value for money? | Update meeting with project leader as required | Project sponsor |
| MMU | Gravemetrics, Raman | Low | Instrument operator,<br>Documentation of data | Problems with flow,<br>Equipment problems | Project steering | Research |
| Sheffield University | Mobile gas analysis | Low | Gas analysis operator,<br>Documentation of data | Problems with flow,<br>Equipment problems | Project steering | Research |
| Manchester University | AMS / SMPS / Data logging | Low | Instrument operator,<br>Documentation of data | Problems with flow,<br>Equipment problems | Project steering | Research |
| Cardiff University | DMS / SN | Med | Instrument operator,<br>Documentation of data | Problems with flow,<br>Equipment problems | Project steering | Research |
| Rolls Royce | Project coordinator | Med | Instrument operator,<br>Documentation of data,<br>Operation of probe | Coordinating measurement,<br>Working environment,<br>Equipment problems | | Project lead / research |
| DLR | MAAP / CO2 / TGA | Med | Instrument operator,<br>Documentation of data | Problems with flow,<br>Equipment problems | Project steering | Research |
| ONERA | TEM / SEM | Low | Instrument operator,<br>Documentation of data | Problems with flow,<br>Equipment problems | Project steering | Research |

**Stakeholder Analysis: Off-wing testing at Rolls Royce, Derby**

| Stakeholder | Stake in the project | Impact | What does the Project expect the Stakeholder to provide? | Perceived attitudes and/or risks | Stakeholder Management Strategy | Responsibility |
|---|---|---|---|---|---|---|
| Rolls Royce | Owner of facility. Operators of test cell. Owner of engines. Project co-ordinator | High | Use of test cell facility, Cost of fuel, Supporting data, Determine procedures, | Technically oriented project What is purpose of data? Concern about increased workload / safety. Will data be commercially sensitive? | Update meeting with project leader as required, Risk assessment package Anonomise data | Project partner / partial sponsor |
| EASA | Funding body, | High | Funding to support the project | Does it achieve objectives? Value for money? | Update meeting with project leader as required | Project sponsor |
| MMU | Gravemetrics, Raman | Low | Instrument operator, Documentation of data | Problems with flow, Equipment problems | Project steering | Research |
| Sheffield University | Mobile gas analysis | Low | Gas analysis operator, Documentation of data | Problems with flow, Equipment problems | Project steering | Research |
| Manchester University | AMS / SMPS / Data logging | Low | Instrument operator, Documentation of data | Problems with flow, Equipment problems | Project steering | Research |
| Cardiff University | DMS / SN | Med | Instrument operator, Documentation of data | Problems with flow, Equipment problems | Project steering | Research |
| DLR | MAAP / CO2 / TGA | Med | Instrument operator, Documentation of data | Problems with flow, Equipment problems | Project steering | Research |
| ONERA | TEM / SEM | Low | Instrument operator, Documentation of data | Problems with flow, Equipment problems | Project steering | Research |

## Summary table of in-service engines for year 2006 (sourced from www.jetinventory.com, subscription required for 2010 data)

| [Engine Model] | [Engine Mfr] | Model | Units |
|---|---|---|---|
| AE3007 | Rolls Royce (Allison) | Embraer RJ | 91 |
| AE3007 | Rolls Royce (Allison) | ERJ | 875 |
| ALF502R | Honeywell (Lycoming) | BAe 146 | 187 |
| BR715A1 | Rolls Royce - Deutschland | 717 | 155 |
| CF34 | General Electric | Canadair Reg. Jet | 1380 |
| CF34 | General Electric | E170 | 152 |
| CF34 | General Electric | E190 | 56 |
| CF34 | General Electric | Embraer E170 | 1 |
| CF6 | General Electric | 747 | 424 |
| CF6 | General Electric | 767 | 590 |
| CF6 | General Electric | A300 | 253 |
| CF6 | General Electric | A310 | 143 |
| CF6 | General Electric | A330 | 129 |
| CF6 | General Electric | DC-10 | 202 |
| CF6 | General Electric | MD-10 | 52 |
| CF6 | General Electric | MD-11 | 117 |
| CFM56 | CFM International | 707 | 41 |
| CFM56 | CFM International | 737 | 4069 |
| CFM56 | CFM International | A318 | 36 |
| CFM56 | CFM International | A319 | 620 |
| CFM56 | CFM International | A320 | 862 |
| CFM56 | CFM International | A321 | 182 |
| CFM56 | CFM International | A340 | 238 |
| CFM56 | CFM International | DC-8 | 83 |
| CONWAY | Rolls Royce | VC10 | 16 |
| GE90 | General Electric | 777 | 231 |
| JT3D | Pratt & Whitney | 707 | 206 |
| JT3D | Pratt & Whitney | 720 | 4 |
| JT3D | Pratt & Whitney | DC-8 | 80 |
| JT4A | Pratt & Whitney | 707 | 3 |
| JT8D | Pratt & Whitney | 707 | 1 |
| JT8D | Pratt & Whitney | 727 | 791 |
| JT8D | Pratt & Whitney | 737 | 738 |
| JT8D | Pratt & Whitney | Caravelle | 2 |
| JT8D | Pratt & Whitney | DC-9 | 531 |
| JT8D | Pratt & Whitney | MD-80 | 1103 |
| JT9D | Pratt & Whitney | 747 | 232 |
| JT9D | Pratt & Whitney | 767 | 81 |
| JT9D | Pratt & Whitney | A300 | 16 |
| JT9D | Pratt & Whitney | A310 | 26 |
| JT9D | Pratt & Whitney | DC-10 | 18 |
| Kuznetsov | KKBM (Kuibyshev) | IL-62 | 43 |
| Kuznetsov | KKBM (Kuibyshev) | IL-86 | 76 |
| Kuznetsov | KKBM (Kuibyshev) | TU-154 | 328 |
| LF507 | Honeywell | BAe 146 | 176 |
| Lotarev | ZKMB Progress(Lotarev) | Yak-42 | 166 |
| PW2000 | Pratt & Whitney | 757 | 428 |
| PW2000 | Pratt & Whitney | IL-96 | 1 |
| PW300 | Pratt & Whitney Canada | AvCraft 328Jet | 106 |
| PW4000 | Pratt & Whitney | 747 | 224 |
| PW4000 | Pratt & Whitney | 767 | 210 |
| PW4000 | Pratt & Whitney | 777 | 156 |
| PW4000 | Pratt & Whitney | A300 | 149 |
| PW4000 | Pratt & Whitney | A310 | 58 |
| PW4000 | Pratt & Whitney | A330 | 133 |
| PW4000 | Pratt & Whitney | MD-11 | 78 |
| RB211 | Rolls Royce | 747 | 172 |
| RB211 | Rolls Royce | 757 | 605 |
| RB211 | Rolls Royce | 767 | 31 |
| RB211 | Rolls Royce | L-1011 | 108 |
| RB211 | Rolls Royce | TU-204 | 7 |
| Soloviev | Perm (JSC Aviadvigatel) | IL-62 | 119 |
| Soloviev | Perm (JSC Aviadvigatel) | IL-96 | 18 |
| Soloviev | Perm (JSC Aviadvigatel) | TU-134 | 452 |
| Soloviev | Perm (JSC Aviadvigatel) | TU-154 | 292 |
| Soloviev | Perm (JSC Aviadvigatel) | TU-204 | 27 |
| SPEY | Rolls Royce | BAC 1-11 | 43 |
| SPEY | Rolls Royce | F28 | 158 |
| TAY651 | Rolls Royce | 727 | 32 |
| TAY650 | Rolls Royce | F100 | 225 |
| TAY620 | Rolls Royce | F100 | 36 |
| TAY620 | Rolls Royce | F70 | 47 |
| TRENT | Rolls Royce | 777 | 216 |
| TRENT | Rolls Royce | A330 | 182 |
| TRENT | Rolls Royce | A340 | 96 |
| V2500 | Int'l Aero Engines | A319 | 309 |
| V2500 | Int'l Aero Engines | A320 | 749 |
| V2500 | Int'l Aero Engines | A321 | 188 |
| V2500 | Int'l Aero Engines | MD-90 | 110 |
| | | | |