

# Volatile Particle Remover Calibration and Validation Procedures

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# Table of contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>VPR Overview</b>	<b>2</b>
2.1	Requirements	2
2.2	Recommended System	2
<b>3</b>	<b>Primary Calibration Methods</b>	<b>4</b>
3.1	Primary Calibration Criteria	4
3.2	Calibration Aerosol	5
3.3	Additional equipment requirements	6
<b>4</b>	<b>Validation Methods</b>	<b>8</b>
4.1	Validation Method Criteria	8
<b>5</b>	<b>Primary Calibration Procedures</b>	<b>10</b>
5.1	Particle concentration reduction factor ( $f_r$ )	10
5.2	Validation of the VPR for volatile particle removal efficiency	12
5.3	Calculation of particle concentration reduction factor ( $f_r$ )	16
5.4	Calculation of removal efficiency of volatile particles	17
<b>6</b>	<b>Validation Procedures</b>	<b>18</b>
6.1	Particle concentration reduction factor ( $f_r$ )	18
6.2	Validation of the VPR for volatile particle removal efficiency	20
6.3	Calculation of particle concentration reduction factor ( $f_r$ )	24
6.4	Calculation of removal efficiency of volatile particles	24
<b>7</b>	<b>References</b>	<b>26</b>
<b>8</b>	<b>Annex 1: example of primary calibration of VPR</b>	<b>27</b>
<b>9</b>	<b>Annex 2: example of particle concentration reduction factors (<math>f_r</math>)</b>	<b>31</b>



# 1 Introduction

Appendix 5 of the 'Proposal for draft supplement 7 to the 05 series of amendments to Regulation No.83'<sup>1</sup> describes a sampling pre-conditioning system to be used for particle number emissions measurements of exhaust emissions after a cold start for type approval testing.

The sampling pre-conditioning unit shall be capable of diluting the sample in one or more stages to achieve a particle number concentration below the threshold of the single particle count mode of the particle number counter and gas temperature below 35°C at the particle number counter. The major component of the sample pre-conditioning system is a Volatile Particle Remover (VPR), which is used to define the nature of the particles to be measured. The version of the VPR described in the recommended system provides heated dilution, thermal conditioning of the sample aerosol, further dilution of particle number concentration and cooling of the sample prior to entry into the particle number counter.

This document describes the calibration and validation procedures for the VPR. Calibration of the VPR is to be performed at the point of manufacture and validation is to be performed 6 monthly for all instruments without automatic temperature sensors or 12 monthly if automatic temperature sensors are present. Should the system 'fail' its validation procedure or the particle number measurement system be modified in any way the calibration procedure must be repeated.

## 2 VPR Overview

### 2.1 Requirements

The specific requirements for the sample preconditioning unit are described in Section 1.3.3 of 'Proposal for draft supplement 7 to the 05 series of amendments to Regulation No.83'<sup>1</sup>(this was further amended in Informal document No. GRPE-54-10<sup>4</sup>, and is included here) (may need to update this reference once a new amendment has been made).

*1.3.3. The sample preconditioning unit shall*

*1.3.3.1. Be capable of diluting the sample in one or more stages to achieve a particle number concentration below the threshold of the single particle count mode of the particle number counter and gas temperature below 35 °C at the particle number counter.*

*1.3.3.2. Include an initial heated dilution stage which outputs a diluted sample at a temperature of  $\geq 150$  °C  $\leq 400$  °C.*

*1.3.3.3. Include elements that operate under conditions to achieve a particle concentration reduction factor ( $f_r$ ) at 30nm<sup>1</sup> and 50nm particle diameters that is within 20 per cent of that at 100nm particle diameter for the sample pre-conditioning unit as a whole.*

*1.3.3.4. Also achieve greater than 99 per cent reduction of an aerosol comprising  $\geq 30$  nm n-C40 alkane particles.*

### 2.2 Recommended System

The following section describes the recommended practice for particle number measurement, taken from Section 1.4, Appendix 5 of the 'Proposal for draft supplement 7 to the 05 series of amendments to Regulation No.83'<sup>1</sup>. However, any sample preconditioning system meeting the requirements detailed in Section 2.1 may be used. The recommended system is illustrated in Figure 1.

*The volatile particle remover (VPR) shall comprise one particle number diluter (PND<sub>1</sub>), an evaporation tube and a second diluter (PND<sub>2</sub>) in series. This dilution function (DF<sub>tot</sub>) is to reduce the number concentration of the sample entering the particle number counter to within the single particle count mode limit of the counter and to suppress nucleation within the sample. DF<sub>tot</sub> is calculated as the product of the dilution factor in the first particle number diluter (PNDF<sub>1</sub>) and the dilution factor in the second particle number diluter (PNDF<sub>2</sub>).*

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<sup>1</sup> All particle diameters referred to in this document are electrical mobility diameters



The VPR shall operate under conditions that achieve greater than 99 per cent reduction of  $\geq 30$  nm C40 particles and achieve a particle concentration reduction factor ( $f_r$ ) at 30nm and 50nm solid particle diameters that is within 20 per cent of that at 100nm solid particle diameter for the sample pre-conditioning unit as a whole.

1.4.4.1. First Particle Number Dilution Device ( $PND_1$ )

The first particle number dilution device shall be specifically designed to dilute particle number concentration and operate at a (wall) temperature of 150 °C - 400 °C. The wall temperature set point should not exceed the wall temperature of the ET (paragraph 1.4.4.2.). The diluter should be supplied with HEPA filtered dilution air and be capable of a minimum dilution factor of 10 times.

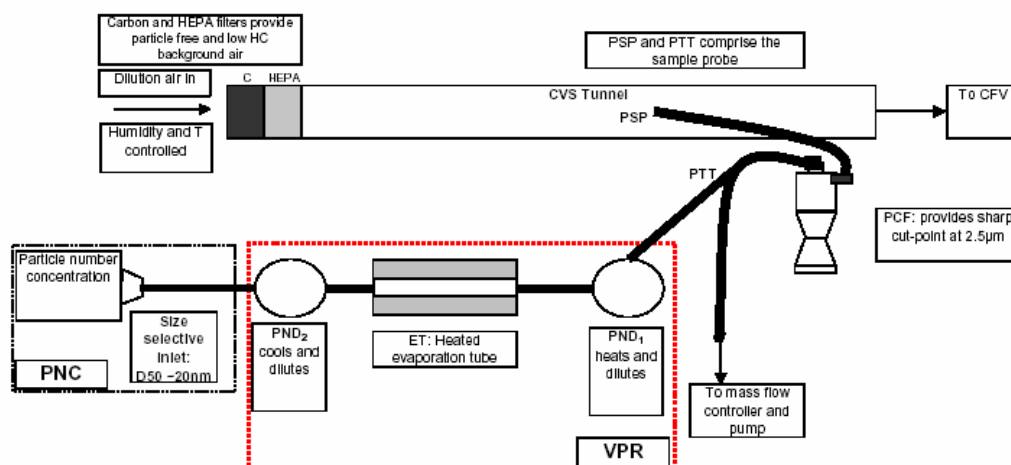
1.4.4.2. Evaporation Tube

The entire length of the ET shall be controlled to a wall temperature greater than or equal to that of the first particle number dilution device and the wall temperature held at a fixed value between 300 °C and 400 °C and within a tolerance of  $\pm 20$  °C.

1.4.4.3. Second Particle Number Dilution Device ( $PND_2$ )

The second particle number dilution device shall be specifically designed to dilute particle number concentration. The diluter shall be supplied with HEPA filtered dilution air and be capable of maintaining a single dilution factor within a range of 10 to 30 times. The dilution factor of  $PND_2$  shall be selected in the range between 10 and 15 such that particle number concentration downstream of the second diluter is within the single particle count mode limit of the particle number counter and the gas temperature prior to entry to the PNC is  $< 35$  °C.

Figure 1: Schematic diagram of particle number emissions measurement system



## 3 Primary Calibration Methods

The following general points are brought to the attention of the reader:

- Principles of good calibration practice should be adopted when using any of the methods described below. In particular, users should ensure that any piece of ancillary equipment that is critical to the calibration is itself appropriately calibrated before use.
- The calibration methods may rely upon comparing the measurements from two pieces of aerosol measurement instrumentation. The user must ensure that the calibration aerosol pathway to each instrument is configured so that any particle deposition that may occur between particle source and instrument is comparable for both instruments. This is usually achieved by ensuring residence time is comparable in both pathways. It may also be necessary to take into account the pathway within each instrument from the inlet to the measurement volume, if there are significant differences between the instruments. A simple method to ensure sample pathways have the same losses is to measure each sample line using one PNC at a high aerosol concentration and check the measured concentration is the same.
- Particle deposition can be minimised by utilizing conductive tubing.
- The term ‘upstream’ refers to the sampling location at the inlet of the VPR ie PND<sub>1</sub> inlet.
- The term ‘downstream’ refers to the sampling location at the outlet of the VPR ie after the second diluter PND<sub>2</sub>.

### 3.1 Primary Calibration Criteria

The VPR must be calibrated in terms of its particle concentration reduction factor ( $f_r$ ) and its volatile particle removal efficiency (or suppression of nucleation particles). The Technical Service shall ensure the existence of a calibration certificate for the VPR demonstrating compliance with a traceable performance specification at the point of manufacture. Annual calibration is not necessary unless major maintenance work has been performed on the VPR or the VPR has failed its validation criteria.

#### 3.1.1 Particle Concentration Reduction Factor ( $f_r$ )

Calibration shall be undertaken by measuring the particle concentration reduction factor ( $f_r$ ) of solid particles with an electrical mobility diameter of 30nm, 50nm and 100nm. Calibration shall be undertaken for at least 5 dilution factors spaced logarithmically across the nominal dilution factor range of the VPR. In the case of VPRs with a variable secondary diluter (PND<sub>2</sub>) the calibration must be performed across a matrix of 15 nominal dilution settings (the 5 settings at PND<sub>1</sub> and 3 settings

(10, 15 and an intermediate setting) at PND<sub>2</sub>). At each nominal dilution setting the overall particle concentration reduction factor ( $f_r$ ) will be defined as the mean of the factors for the electrical mobility particle diameters 30nm, 50nm and 100nm, with a requirement that the particle concentration reduction factor ( $f_r$ ) at 30nm and 50nm is within 20% of that at 100nm.

Calibration shall be conducted at the instrument manufacturer's recommended operating conditions.

### **3.1.2 Volatile Particle Removal Efficiency**

The VPR shall demonstrate greater than 99 per cent reduction of monodisperse  $\geq 30$  nm n-C40 alkane particles ( $GSD \leq 1.2$ ) at an upstream particle concentration of a minimum of 10,000/cm<sup>3</sup> when operated at the following conditions: manufacturer's recommended evaporation tube temperature, PND<sub>2</sub> at its fixed nominal dilution setting or the nominal secondary dilution factor of 10 for variable diluters, and the lowest PND<sub>1</sub> nominal dilution setting.

## **3.2 Calibration Aerosol**

### **3.2.1 Solid particles**

There are a number of aerosol generation techniques that are capable of producing solid particles in the size range between 30 and 100nm diameter including condensation generators, combustion aerosol generators, nebulisation and hot wires<sup>5</sup>. Any of these methods are suitable for producing calibration aerosols, but for the VPR calibration they must meet the following criteria:

- Capable of producing a stable aerosol at a minimum concentration of 5,000 particles/cm<sup>3</sup> and below the single particle count mode limit of the particle number counter.
- Monodispersity:  $GSD \leq 1.2$
- Relative humidity <50%

Any calibration aerosol must be stable at VPR operating conditions ie it should be physically and chemically stable and its aerodynamic behaviour should not change at ET operating temperatures.

A common aerosol used for instrument calibration is sodium chloride. This is well characterised, inexpensive and relatively safe to use compared with other aerosols. Sodium chloride particles may be generated using a number of the techniques listed above.

### **3.2.2 Volatile particles**

The requirement for volatile particles is more prescriptive than for solid particles, these are:

- Tetracontane (C<sub>40</sub>) particles with a diameter of  $\geq 30\text{nm}$  at concentrations  $\geq 10,000$  particles/cm<sup>3</sup>.
- Monodispersity: GSD  $\leq 1.2$

A condensation generator is a simple method to produce these particles. The monodispersity of the aerosol (for both solid and volatile particles) should be verified if it is not defined by the aerosol generator itself. A technique for producing solid and volatile particles is described in the example of Annex 1. Alternative methods that generate similarly sized particles and concentrations are equally appropriate.

### **3.3 Additional equipment requirements**

The following table details the equipment, along with their purposes, that are additional to the components of the particle number measurement system and are recommended requirements for successful calibration of the volatile particle remover (Table 1).

**Table 1: Description of equipment required for calibration of the VPR**

<b>Required equipment</b>	<b>Purpose</b>
1 calibrated flow meter	Measurement of particle counter flow
1 HEPA filter (at least 99.99% efficiency)	Zero checks on PNC and VPR
Aerosol generator(s)	To generate solid and volatile particles for VPR performance checks
1 neutraliser	Neutralisation of charges on aerosol for calibration
<b><i>Optional</i></b>	
Calibrated Electrostatic Classifier/Scanning Mobility Particle Sizer	Production of monodisperse aerosols. Other instruments may be used to produce monodisperse particles but an SMPS may be required to verify the GSD.
Additional calibrated PNC	For simultaneous measurements of upstream and downstream particle number concentration for VPR performance checks.
Calibrated flow meter and pump	To simulate downstream PNC flow from VPR whilst taking upstream measurements if calibrating the VPR with one PNC.

## 4 Validation Methods

The following general points are brought to the attention of the reader:

- Principles of good calibration practice should be adopted when using any of the methods described below. In particular, users should ensure that any piece of ancillary equipment that is critical to the validation is appropriately calibrated before use.
- The validation methods may rely upon comparing the measurements from two pieces of aerosol measurement instrumentation. The user must ensure that the validation aerosol pathway to each instrument is configured so that any particle deposition that may occur between particle source and instrument is comparable for both instruments. This is usually achieved by ensuring residence time is comparable in both pathways. It may also be necessary to take into account the pathway within each instrument from the inlet to the measurement volume, if there are significant differences between the instruments.
- Particle deposition can be minimised by utilizing conductive tubing.
- The term ‘upstream’ refers to the sampling location at the inlet of the VPR ie PND<sub>1</sub> inlet.
- The term ‘downstream’ refers to the sampling location at the outlet of the VPR ie after the second diluter PND<sub>2</sub>.

### 4.1 Validation Method Criteria

The VPR must be validated in terms of its particle concentration reduction factor ( $f_r$ ) and its volatile particle removal efficiency (or suppression of nucleation particles).

The Technical Service shall ensure the existence of a validation certificate of the volatile particle remover within a 6-month period prior to the emissions test. If the volatile particle remover incorporates temperature monitoring alarms a 12-month validation interval shall be permissible.

#### 4.1.1 Particle Concentration Reduction Factor ( $f_r$ )

Validation shall be undertaken by measuring the particle concentration reduction factor ( $f_r$ ) of solid particles with an electrical mobility diameter of 30nm, 50nm and 100nm. Validation shall be undertaken at one dilution setting typical for DPF exhaust emissions measurement.

The validation acceptance criterion is that the validation measurement is  $\pm 10\%$  of the particle concentration reduction factor ( $f_r$ ) as determined during the primary calibration. (note: to be reviewed following calibration measurement exercise).

#### **4.1.2 Volatile Particle Removal Efficiency**

The VPR shall demonstrate greater than 99 per cent reduction of monodisperse  $\geq 30$  nm n-C40 alkane particles ( $GSD \leq 1.2$ ) at an upstream particle concentration of a minimum of  $10,000/\text{cm}^3$  when operated at the following conditions: manufactureres recommended evaporation tube temperature,  $PND_2$  at its fixed nominal dilution setting or the nominal secondary dilution factor of 10 for variable diluters, and the lowest  $PND_1$  nominal dilution setting.

The validation aerosol and equipment requirements are identical to those described for primary calibration in Sections 3.2 and 3.3.

## 5 Primary Calibration Procedures

The procedures for performing a VPR calibration are described below. For all calibration and validation procedures a stable aerosol is defined as having an upstream concentration drift of less than 10% over a 5 minute period.

### 5.1 Particle concentration reduction factor ( $f_r$ )

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 PNC 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 PNC to verify that the upstream concentration hasn't drifted (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 PNCs (at the inlet and outlet of the VPR), has been confirmed before this procedure commences using the secondary calibration method described in the 'Condensation Particle Counter Calibration Procedures<sup>3</sup>' document. The PNC's response at all particle diameters (30, 50 and 100nm) must be measured. One PNC must be adjusted to take into consideration any differences between the two instruments. If you are using two different models of PNCs please note their counting efficiency may differ significantly for 30nm diameter particles.

Prepare the VPR and PNCs for use:

- a. Position all apparatus according to your manufacturers instructions, this will be generally similar to that described in the example, Annex 1, Figure 2.
- b. Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (eg 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 (eg replacement of filters, tubing etc).
- d. Switch on the electrostatic classifier (or other source of monodisperse particles), PNCs and VPR.
- e. Fill the PNCs with working fluid and allow the saturator and condenser to reach their specified temperatures.
- f. Apply an external vacuum source to the PNCs if not fitted with an internal pump.
- g. Do not proceed unless all indicators on the PNCs show correct instrument status (eg temperature, liquid level, flow and laser etc).



- h. Check the inlet flow rates of the PNCs with an appropriate calibrated flow meter (low pressure drop variety recommended, eg 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 of at least 99.99 percent efficiency is attached to the inlet of the PNCs. The PNC requires attention from the manufacturer if concentrations greater than  $0.5 \text{ particles/cm}^3$  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 to reach specified temperatures.
- l. Connect the PNC to the VPR.
- m. When the VPR has reached its specified temperature settings connect a HEPA filter of at least 99.99 percent efficiency to the inlet and ensure a zero concentration is reported on the PNC. Do not proceed if particle concentrations of greater than  $1 \text{ particles/cm}^3$  are reported.
- n. If you are using one PNC for the calibration 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 PNC from the VPR. If you are using two PNCs split the flow from the neutraliser between the upstream PNC and the inlet of the VPR.

*Note: if an aerosol generator which produces monodisperse 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 pipework from the neutraliser to both the upstream PNC 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 monodisperse aerosol flow leaving the classifier is sufficient for the total inlet flow of both the PNC and the VPR (provide additional particle-free flow after the classifier if necessary).

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

Generate the calibration aerosol and connect the electrostatic classifier to the source.

- q. Select a nominal dilution setting on  $\text{PND}_1$ .
- r. For variable  $\text{PND}_2$  diluters select a nominal dilution setting on  $\text{PND}_2$ .
- s. Select a monodisperse diameter (30, 50 or 100nm) using the electrostatic classifier and allow the number concentration to stabilise upstream of the VPR. All monodisperse particles must enter the VPR at concentrations of greater than  $5000 \text{ particles/cm}^3$ . Once stable record measurements for 10 minutes up and downstream of the VPR
- t. Once a stable measurement has been taken select the next nominal dilution setting on  $\text{PND}_1$ , allow to stabilise and record measurements for 10 minutes up and downstream of the VPR.
- u. Repeat step (t) until all 5 dilution settings of  $\text{PND}_1$  have been measured.

- v. For variable PND<sub>2</sub> diluters, select the next nominal dilution setting, and repeat the measurements for all five dilution settings on PND<sub>1</sub>.
- w. Select the third and final nominal dilution setting on PND<sub>2</sub> and repeat the measurements for all five dilution settings on PND<sub>1</sub>.

*Note: The minimum number of measurement conditions per particle diameter should be 15 for a variable secondary diluter, for a fixed secondary diluter the minimum number of measurement conditions should be five per particle diameter.*

- x. The next monodisperse diameter should be selected on the electrostatic classifier and allowed to stabilise. Repeat steps (s) to (w) for each monodisperse diameter.
- y. If you are using one PNC 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, eg measure upstream concentration for 10 minutes, measure the downstream concentration for 10 minutes, then return to the upstream sampling arrangement and sample for 10 minutes to ensure the concentration is stable. Measurement is valid if upstream particle concentration has within  $\pm 10\%$  of initial reading.

*Note: According to Poisson Statistics a sample duration of 10 minutes at a particle concentration of 0.6 particles/cm<sup>3</sup> and sampling at a flow rate of 1 lmin<sup>-1</sup> produces data within the 95% confidence limit at an accuracy of 2.5%, therefore a 10 minute sample duration is sufficient for all measurements required in this procedure.*

Once all required diameters and nominal dilution settings have been measured the aerosol source should be disconnected from the VPR and a HEPA filter applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 1 particle/cm<sup>3</sup>). This ensures the VPR has not become contaminated from the calibration procedure.

## 5.2 Validation of the VPR for volatile particle removal efficiency

For this validation only one monodisperse diameter is required,  $\geq 30\text{nm}$  (tetracontane, C<sub>40</sub>) at an inlet concentration at the VPR of  $>10,000$  particles/cm<sup>3</sup>.

The VPR is validated at one nominal dilution setting, PND<sub>1</sub> should be at the lowest setting and for variable PND<sub>2</sub> diluters a nominal dilution setting of 10 should be used. The evaporation tube should be at the operating conditions recommended by the manufacturer (and that most commonly used for DPF exhaust emissions measurements).

There are two methods for measurement of volatile particle removal efficiency:

### **Method 1 - Measurement of up and downstream particle concentrations using a PNC**

This can be the PNC supplied with the particle number measurement system. For the volatile particle removal efficiency calibration an upstream concentration of  $>10,000$  particles/cm<sup>3</sup> is required, however this concentration may be above the full scale deflection of the PNC in single particle count mode. An assumption can be made that any measurement by the PNC above this limit ensures the VPR is challenged with a minimum of 10,000 particles/cm<sup>3</sup>. The procedure for this method is as follows (this validation can be performed with either one or two PNCs, if two PNCs are used their response at all particle diameters (30, 50 and 100nm), must be compared using the secondary calibration method described in the 'Condensation Particle Counter Calibration Procedures<sup>3</sup>' document. One PNC must be adjusted to take into consideration any differences between the two instruments. If you are using two different models of PNCs please note their counting efficiency may differ significantly for 30nm diameter particles.

Prepare the VPR and PNCs for use:

- a. Position all apparatus according to your manufacturers instructions, this will be generally similar to that described in the example, Annex 1, Figure 2.
- b. Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (eg 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 (eg replacement of filters, tubing etc).
- d. Switch on the electrostatic classifier (or other source of monodisperse particles), PNCs and VPR.
- e. Fill the PNCs with working fluid and allow the saturator and condenser to reach their specified temperatures.
- f. Apply an external vacuum source to the PNCs if not fitted with an internal pump.
- g. Do not proceed unless all indicators on the PNCs show correct instrument status (eg temperature, liquid level, flow and laser etc).
- h. Check the inlet flow rates of the PNCs with an appropriate calibrated flow meter (low pressure drop variety recommended, eg 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 of at least 99.99 percent efficiency is attached to the inlet of the PNCs. The PNC requires attention from the manufacturer if concentrations greater than 0.5 particles/cm<sup>3</sup> 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 to reach specified temperatures.
- l. Connect the PNC to the VPR.
- m. When the VPR has reached its specified temperature settings connect a HEPA filter of at least 99.99 percent efficiency to the inlet and ensure a zero concentration is reported on the PNC. Do not proceed if particle concentrations of greater than 1 particles/cm<sup>3</sup> are reported.

- n. If you are using one PNC for the volatile particle calibration 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 PNC from the VPR. If you are using two PNCs split the flow from the neutraliser between the upstream PNC and the inlet of the VPR.

*Note: if an aerosol generator which produces monodisperse 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 pipework from the neutraliser to both the upstream PNC 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 monodisperse aerosol flow leaving the classifier is sufficient for the total inlet flow of both the PNC and the VPR (provide additional particle-free flow after the classifier if necessary).

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

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

- q. Select 30nm diameter particles using the electrostatic classifier and allow the number concentration to stabilise upstream of the VPR. Once stable record measurements for 10 minutes up and downstream of the VPR
- r. If you are using one PNC 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, eg measure upstream concentration for 10 minutes, measure the downstream concentration for 10 minutes, then return to the upstream sampling arrangement and sample for 10 minutes to ensure the concentration is stable. The drift of the upstream aerosol concentration must not be more than 10%.

Once complete the aerosol source should be disconnected from the VPR and a HEPA filter applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 1 particle/cm<sup>3</sup>). This ensures the VPR has not become contaminated from the validation procedure.

### **Method 2 - One PNC measuring downstream of the VPR only**

The particle counter used for this method can be the PNC supplied with the particle number measurement system. The procedure for this method is as follows:

Prepare the VPR and PNCs for use:

- a. Position all apparatus according to your manufacturers instructions, this should be something similar to that described in the example, Annex 1, Figure 2.
- b. Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (eg 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 (eg replacement of filters, tubing etc).
- d. Switch on the electrostatic classifier (or other source of monodisperse particles), PNC and VPR.
- e. Fill the PNC with working fluid and allow the saturator and condenser to reach their specified temperatures.
- f. Apply an external vacuum source to the PNC if not fitted with an internal pump.
- g. Do not proceed unless all indicators on the PNC show correct instrument status (eg temperature, liquid level, flow and laser etc).
- h. Check the inlet flow rates of the PNC with an appropriate calibrated flow meter (low pressure drop variety recommended, eg 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 of at least 99.99 percent efficiency is attached to the inlet of the PNC. The PNC requires attention from the manufacturer if concentrations greater than  $0.5 \text{ particles/cm}^3$  are reported.
- j. If required, apply clean dry filtered air to the VPR at pressures specified by the manufacturer.
- k. Connect the PNC to the VPR.
- l. Do not heat the VPR, leave it at room temperature.
- m. Connect a HEPA filter of at least 99.99 percent efficiency to the inlet of the VPR and ensure a zero concentration is reported on the PNC. Do not proceed if particle concentrations of greater than  $1 \text{ particles/cm}^3$  are reported.

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

- 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).

Make arrangements to log data from the PNC.

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

- o. Select 30nm using the electrostatic classifier and allow to stabilise for at least 10 minutes. The monodisperse particles must enter the VPR at concentrations of greater than  $10,000 \text{ particles/cm}^3$ . Once stable record measurements for 10 minutes downstream of the VPR

- 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 30nm tetracontane particles to the VPR and record the particle concentration from the PNC (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 10 minute period.

Once complete the aerosol source should be disconnected from the VPR and a HEPA filter applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 1 particle/cm<sup>3</sup>). This ensures the VPR has not become contaminated from the validation procedure.

### 5.3 Calculation of particle concentration reduction factor ( $f_r$ )

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

Particle Concentration Reduction Factor for a given particle diameter and nominal dilution setting,

$$f_r(d) = N_{in}/N_{out} \quad (1)$$

where  $N_{in}$  = upstream/inlet number concentration averaged over the 10 minute stable period and  
 $N_{out}$  = downstream/outlet number concentration averaged over the 10 minute stable period.

For each nominal dilution setting the mean particle concentration reduction factor ( $f_r$ ) should then be calculated for all particle diameters:

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

The performance requirement for the VPR is that  $f_r(30nm)$  and  $f_r(50nm)$  to be within 20% of  $f_r(100nm)$ , ie

$$f_r(30nm)/f_r(100nm) > 0.8 \quad (3)$$

$$f_r(50nm)/f_r(100nm) > 0.8 \quad (4)$$

Each VPR will therefore have a minimum of five particle concentration reduction factors ( $f_r$ ) corresponding to 5 nominal dilution settings. For VPRs with a variable secondary diluter (PND<sub>2</sub>) fifteen particle concentration reduction factors ( $f_r$ ) will be produced. Some examples of the particle concentration reduction factors are shown in Table 3, Annex 2. (to be completed following the measurement work)

## 5.4 Calculation of removal efficiency of volatile particles

There are two methods to calculate the removal efficiency of volatile particles depending on which validation method was adopted:

### 5.4.1 Method 1

The average number concentration of volatile particles at the inlet of the VPR should be calculated over the 10 minute stable period. The performance requirement of the VPR is that >99% of tetracontane particles are removed. Therefore the pass criteria 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 10 minute 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 30nm, for the same nominal dilution settings used in the primary calibration with solid particles.

Volatile Particle Removal Efficiency Criteria =

$$\text{Average Downstream Concentration} \cdot f_r(30\text{nm}) \leq \frac{\text{Average Upstream Concentration}}{100}$$

$f_r(30\text{nm})$  = particle concentration reduction factor at 30nm and the same nominal dilution settings.

### 5.4.2 Method 2

The average number concentration of volatile particles downstream of the VPR should be calculated over the 10 minute stable period for both temperature conditions ie room temperature and heated.

Volatile Particle Removal Efficiency Acceptance Criteria :

$$\text{Average Downstream Concentration (HT)} \leq \frac{\text{Average Downstream Concentration (RT)}}{100}$$

where RT = room temperature VPR  
HT = heated VPR

## 6 Validation Procedures

The procedures for performing a VPR validation are described below. For all procedures a stable aerosol is defined as having an upstream concentration drift of less than 10% over a 5 minute period.

### 6.1 Particle concentration reduction factor ( $f_r$ )

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 PNC 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 PNC to verify that the upstream concentration hasn't drifted 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 PNCs (at the inlet and outlet of the VPR), has been confirmed before this procedure commences using the secondary calibration method described in the 'Condensation Particle Counter Calibration Procedures<sup>3</sup>' document. The PNC's response at all particle diameters (30, 50 and 100nm) must be measured. One PNC must be adjusted to take into consideration any differences between the two instruments. If you are using two different models of PNCs please note their counting efficiency may differ significantly for 30nm diameter particles.

Prepare the VPR and PNCs for use:

- a. Position all apparatus according to the manufacturers instructions, this will be generally similar to that described in the example, Annex 1, Figure 2.
- b. Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (eg 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 (eg replacement of filters, tubing etc).
- d. Switch on the electrostatic classifier (or other source of monodisperse particles), PNCs and VPR.
- e. Fill the PNCs with working fluid and allow the saturator and condenser to reach their specified temperatures.
- f. Apply an external vacuum source to the PNCs if not fitted with an internal pump.
- g. Do not proceed unless all indicators on the PNCs show correct instrument status (eg temperature, liquid level, flow and laser etc).



- h. Check the inlet flow rates of the PNCs with an appropriate calibrated flow meter (low pressure drop variety recommended, eg 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 of at least 99.99 percent efficiency is attached to the inlet of the PNCs. The PNC requires attention from the manufacturer if concentrations greater than  $0.5 \text{ particles/cm}^3$  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 to reach specified temperatures.
- l. Connect the PNC to the VPR.
- m. When the VPR has reached its specified temperature settings connect a HEPA filter of at least 99.99 percent efficiency to the inlet and ensure a zero concentration is reported on the PNC. Do not proceed if particle concentrations of greater than  $1 \text{ particles/cm}^3$  are reported.
- n. If you are using one PNC 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 PNC from the VPR. If you are using two PNCs split the flow from the neutraliser between the upstream PNC and the inlet of the VPR.

*Note: if an aerosol generator which produces monodisperse 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 pipework from the neutraliser to both the upstream PNC 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 monodisperse aerosol flow leaving the classifier is sufficient for the total inlet flow of both the PNC and the VPR (provide additional particle-free flow after the classifier if necessary).

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

- q. Generate the validation aerosol and connect the electrostatic classifier to the source.
- r. Select nominal dilution settings on PND<sub>1</sub> and PND<sub>2</sub> typically used for DPF exhaust emissions measurements.
- s. Select a monodisperse diameter (30, 50 or 100nm) using the electrostatic classifier and allow the number concentration to stabilise upstream of the VPR. All monodisperse particles must enter the VPR at concentrations of greater than  $5000 \text{ particles/cm}^3$ . Once stable record measurements for 10 minutes up and downstream of the VPR
- t. The next monodisperse diameter should then be selected on the electrostatic classifier and allowed to stabilise. Repeat step (s) for each monodisperse diameter.

- u. If you are using one PNC 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, eg measure upstream concentration for 10 minutes, measure the downstream concentration for 10 minutes, then return to the upstream sampling arrangement and sample for 10 minutes to ensure the concentration is stable. Measurement is valid if upstream particle concentration has within  $\pm 10\%$  of initial reading.

Once all required diameters have been measured the aerosol source should be disconnected from the VPR and a HEPA filter applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 1 particle/cm<sup>3</sup>). This ensures the VPR has not become contaminated from the calibration procedure.

## 6.2 Validation of the VPR for volatile particle removal efficiency

For this validation only one monodisperse diameter is required,  $\geq 30\text{nm}$  (tetracontane, C<sub>40</sub>) at an inlet concentration at the VPR of  $>10,000$  particles/cm<sup>3</sup>.

The VPR should be validated at one nominal dilution setting, PND<sub>1</sub> should be at the lowest setting and for variable PND<sub>2</sub> diluters a nominal dilution setting of 10 should be used. The evaporation tube should be at the operating conditions recommended by the manufacturer (and that most commonly used for DPF exhaust emissions measurements).

There are two methods for measurement of volatile particle removal efficiency:

### Method 1 - Measurement of up and downstream particle concentrations using a PNC

This can be the PNC supplied with the particle number measurement system. For the volatile particle removal efficiency validation an upstream concentration of  $>10,000$  particles/cm<sup>3</sup> is required, however this concentration will result in coincidence errors to be introduced into the PNC measurement. An assumption can be made that any measurement by the PNC above this limit ensures the VPR is challenged with a minimum of 10,000 particles/cm<sup>3</sup>. The procedure for this method is as follows (this validation can be performed with either one or two PNCs, if two PNCs are used their response at all particle diameters (30, 50 and 100nm), must be measured using the secondary calibration method described in the 'Condensation Particle Counter Calibration Procedures'<sup>3</sup> document. One PNC must be adjusted to take into consideration any differences between the two instruments. If you are using two different models of PNCs please note their counting efficiency may differ significantly for 30nm diameter particles.

Prepare the VPR and PNCs for use:

- a. Position all apparatus according to your manufacturers instructions, this will be generally similar to that described in the example, Annex 1, Figure 2.

- b. Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (eg 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 (eg replacement of filters, tubing etc).
- d. Switch on the electrostatic classifier (or other source of monodisperse particles), PNCs and VPR.
- e. Fill the PNCs with working fluid and allow the saturator and condenser to reach their specified temperatures.
- f. Apply an external vacuum source to the PNCs if not fitted with an internal pump.
- g. Do not proceed unless all indicators on the PNCs show correct instrument status (eg temperature, liquid level, flow and laser etc).
- h. Check the inlet flow rates of the PNCs with an appropriate calibrated flow meter (low pressure drop variety recommended, eg 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 of at least 99.99 percent efficiency is attached to the inlet of the PNCs. The PNC requires attention from the manufacturer if concentrations greater than 0.5 particles/cm<sup>3</sup> 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 to reach specified temperatures.
- l. Connect the PNC to the VPR.
- m. When the VPR has reached its specified temperature settings connect a HEPA filter of at least 99.99 percent efficiency to the inlet and ensure a zero concentration is reported on the PNC. Do not proceed if particle concentrations of greater than 1 particles/cm<sup>3</sup> are reported.
- n. If you are using one PNC for the volatile particle 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 PNC from the VPR. If you are using two PNCs split the flow from the neutraliser between the upstream PNC and the inlet of the VPR.

*Note: if an aerosol generator which produces monodisperse 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 pipework from the neutraliser to both the upstream PNC 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 monodisperse aerosol flow leaving the classifier is sufficient for the total inlet flow of both the PNC and the VPR (provide additional particle-free flow after the classifier if necessary).

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

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

- q. Select 30nm diameter particles using the electrostatic classifier and allow the number concentration to stabilise upstream of the VPR. Once stable record measurements for 10 minutes up and downstream of the VPR
- r. If you are using one PNC 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, eg measure upstream concentration for 10 minutes, measure the downstream concentration for 10 minutes, then return to the upstream sampling arrangement and sample for 10 minutes to ensure the concentration is stable. The drift of the upstream aerosol concentration must not be more than 10%.

Once complete the aerosol source should be disconnected from the VPR and a HEPA filter applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 1 particle/cm<sup>3</sup>). This ensures the VPR has not become contaminated from the calibration procedure.

### **Method 2 - One PNC measuring downstream of the VPR only**

The particle counter used for this method can be the PNC supplied with the particle number measurement system. The procedure for this method is as follows:

Prepare the VPR and PNCs for use:

- a. Position all apparatus according to the manufacturers instructions, this should be something similar to that described in the example, Annex 1, Figure 2.
- b. Where appropriate clean any dilution mechanisms within the VPR as advised by the manufacturer (eg 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 (eg replacement of filters, tubing etc).
- d. Switch on the electrostatic classifier (or other source of monodisperse particles), PNC and VPR.
- e. Fill the PNC with working fluid and allow the saturator and condenser to reach their specified temperatures.
- f. Apply an external vacuum source to the PNC if not fitted with an internal pump.
- g. Do not proceed unless all indicators on the PNC show correct instrument status (eg temperature, liquid level, flow and laser etc).

- h. Check the inlet flow rates of the PNC with an appropriate calibrated flow meter (low pressure drop variety recommended, eg 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 of at least 99.99 percent efficiency is attached to the inlet of the PNC. The PNC requires attention from the manufacturer if concentrations greater than 0.5 particles/cm<sup>3</sup> are reported.
- j. If required, apply clean dry filtered air to the VPR at pressures specified by the manufacturer.
- k. Connect the PNC to the VPR.
- l. Do not heat the VPR, leave it at room temperature.
- m. Connect a HEPA filter of at least 99.99 percent efficiency to the inlet of the VPR and ensure a zero concentration is reported on the PNC. Do not proceed if particle concentrations of greater than 1 particles/cm<sup>3</sup> are reported.

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

- 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).

Make arrangements to log data from the PNC.

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

- o. Select 30nm using the electrostatic classifier and allow to stabilise for at least 10 minutes. The monodisperse particles must enter the VPR at concentrations of greater than 10,000 particles/cm<sup>3</sup>. Once stable record measurements for 10 minutes downstream of the VPR
- 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 30nm tetracontane particles to the VPR and record the particle concentration from the PNC (at the downstream location).
- r. When a stable downstream concentration is achieved, and the VPR has reached its temperature settings, record the downstream number concentration over a 10 minute period.

Once complete the aerosol source should be disconnected from the VPR and a HEPA filter applied to the inlet to remove all particles from the system and to verify the zero concentration leaving the VPR (should be less than 1 particle/cm<sup>3</sup>). This ensures the VPR has not become contaminated from the calibration procedure.

## 6.3 Calculation of particle concentration reduction factor ( $f_r$ )

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

Particle Concentration Reduction Factor for a given particle diameter:

$$f_r(d) = N_{in}/N_{out} \quad (1)$$

where  $N_{in}$  = upstream/inlet number concentration averaged over the 10 minute stable period and  
 $N_{out}$  = downstream/outlet number concentration averaged over the 10 minute stable period.

The mean particle concentration reduction factor ( $f_r$ ) should then be calculated for all particle diameters:

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

The requirement for successful validation of the VPR is that the measured  $f_r$  is  $\pm 10\%$  of the particle concentration reduction factor ( $f_r$ ) measured during the primary calibration (at the same nominal dilution setting).

If this requirement has not been met, the primary calibration should be repeated.

## 6.4 Calculation of removal efficiency of volatile particles

There are two methods to calculate the removal efficiency of volatile particle depending on which validation method was adopted:

### 6.4.1 Method 1

The average number concentration of volatile particles at the inlet of the VPR should be calculated over the 10 minute stable period. The performance requirement of the VPR is that >99% of tetracontane particles are removed. Therefore the pass criteria 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 10 minute 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 30nm, for the same nominal dilution settings used in the primary calibration with solid particles.

Volatile Particle Removal Efficiency Criteria =

$$\text{Average Downstream Concentration} \cdot f_r(30\text{nm}) \leq \frac{\text{Average Upstream Concentration}}{100}$$

$f_r(30\text{nm})$  = particle concentration reduction factor at 30nm and the same nominal dilution settings.

#### **6.4.2 Method 2**

The average number concentration of volatile particles downstream of the VPR should be calculated over the 10 minute stable period for both temperature conditions ie room temperature and heated.

Volatile Particle Removal Efficiency Acceptance Criteria :

$$\text{Average Downstream Concentration (HT)} \leq \frac{\text{Average Downstream Concentration (RT)}}{100}$$

where RT = room temperature VPR  
HT = heated VPR

## 7 References

<sup>1</sup> Amendments to UNECE Regulations, Regulation No. 83, Proposal for draft supplement 7 to the 05 series of amendments to Regulation No.83, ECE/TRANS/WP.29/GRPE/2007/8

<sup>2</sup>Andersson JD, Clark D UN-GRPE PMP Phase 3 Inter-laboratory Correlation Exercise: Framework and Laboratory Guide, A Document For The UK Department for Transport. RD 04/80801.5

<sup>3</sup>Marshall, IA Particle Number Counters Calibration/Validation Procedures, report to Department for Transport, ED47382004/PNC, Draft Revision 4, August 2007.

<sup>4</sup>UK Proposal to amend document ECE/TRANS/WP.29/GRPE/2007/8, Informal document no. GRPE-54-10.

<sup>5</sup>VDI Guideline 3491 Parts 1 to 16, The Association of German Engineers.  
<http://www.vdi.de/index.php?id=301> (references to be checked)

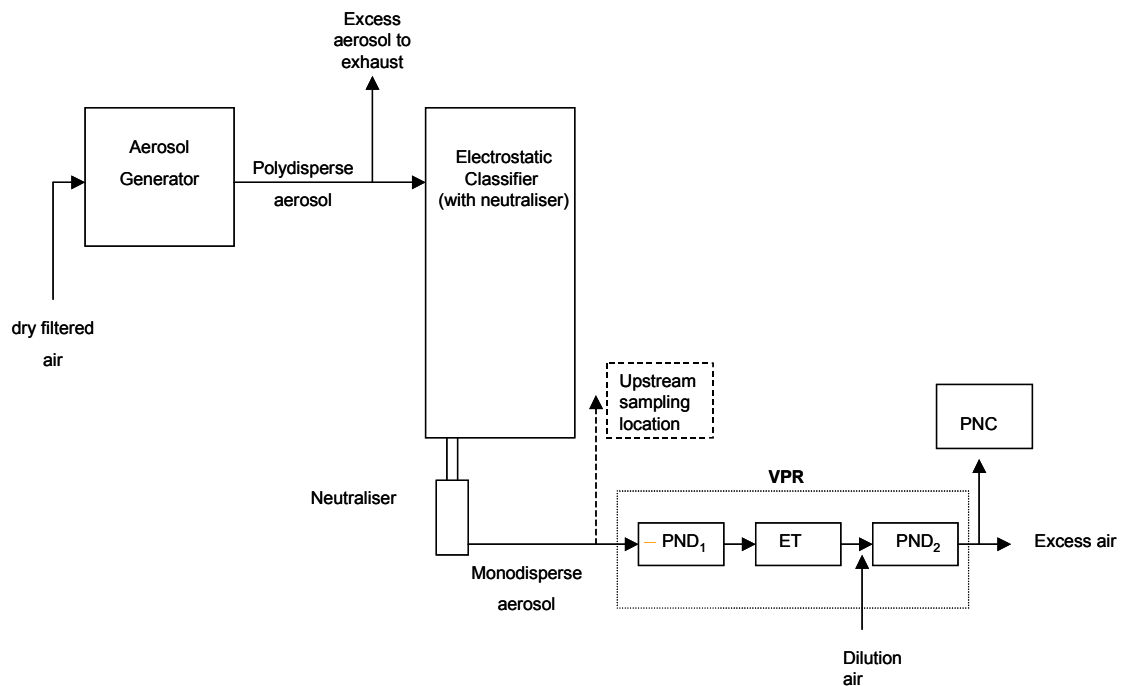
Update references for R83 once amendment has been published.



## 8 Annex 1: example of primary calibration of VPR

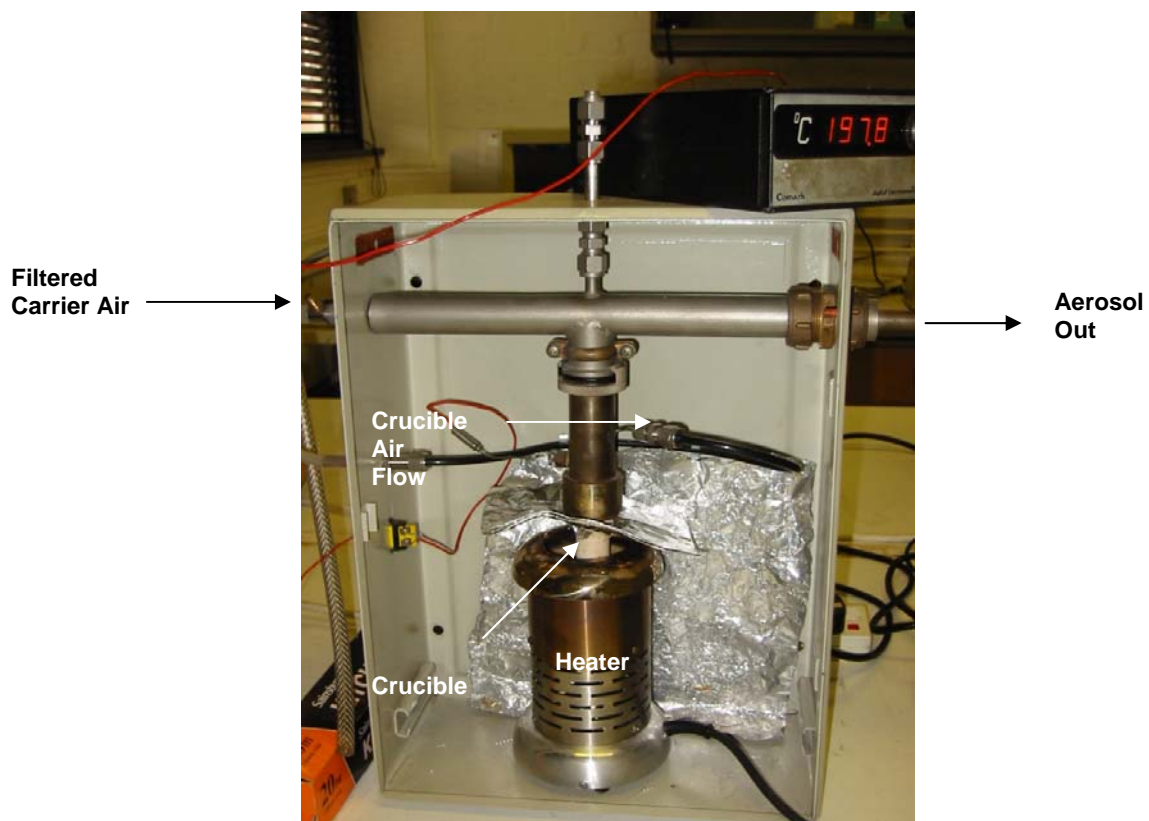
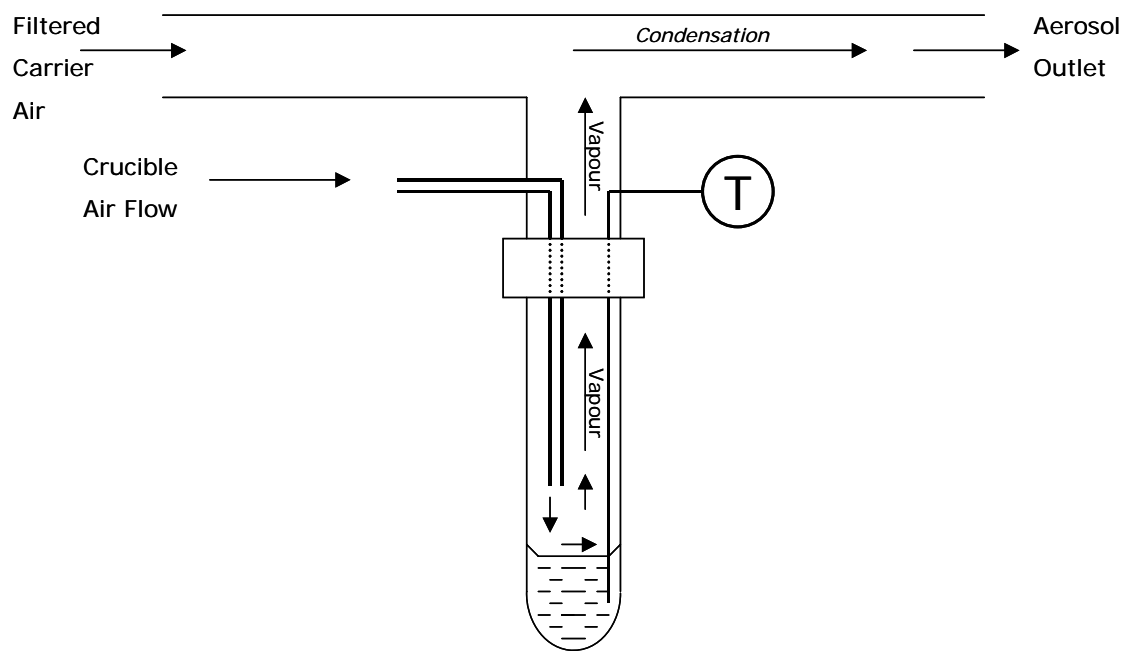
The following example describes one method for calibrating the VPR. The experimental set-up is illustrated in Figure 2.

Figure 2: Calibration of the VPR

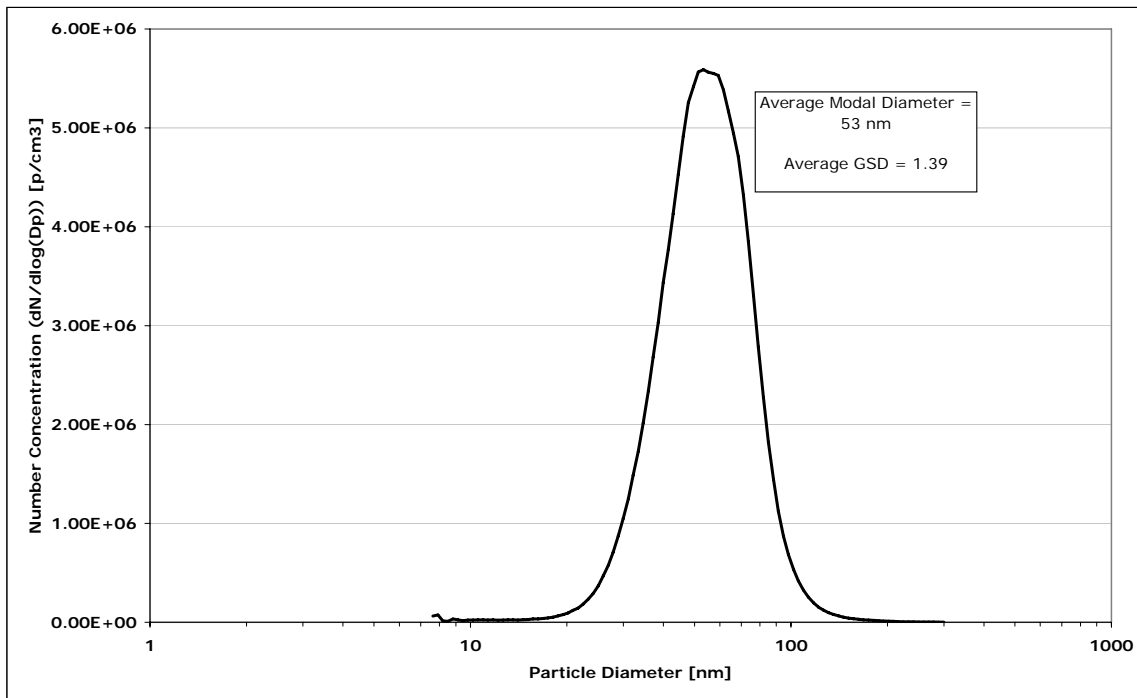


The aerosol generator consisted of a ceramic crucible heated via an electric Bunsen (Figure 3). The bulk material (sodium chloride for particle concentration reduction factor measurement and tetracontane for volatile particle removal efficiency) was placed in the ceramic crucible and heated to near its boiling point. A small flow was introduced into the crucible to displace vapour from the surface of the bulk material to a cooler region of the generator where condensation occurred. Particle diameters were varied by controlling the rate of vapour transport from the crucible (via the crucible air flow) and/or the subsequent cooling rate of the vapour (via the carrier air flow). A typical polydisperse size distribution (before selection of a monodisperse fraction) of a generated sodium chloride aerosol is presented in Figure 4.

**Figure 3: Condensation Aerosol Generator**



**Figure 4** Typical size distribution of a polydisperse sodium chloride calibration aerosol



*Note: This aerosol generation method is reported purely as an example. Alternative methods that generate similarly sized particles and concentrations are equally appropriate.*

The electrostatic classifier was used to select monodisperse fractions of the polydisperse calibration aerosol and deliver the required number concentrations to the VPR (> 5000 particles cm<sup>-3</sup> for sodium chloride and >10,000 particles cm<sup>-3</sup> for tetracontane), reducing the GSD (geometric standard deviation) to around 1.2.

Two PNCs were used to simultaneously record the number concentrations upstream (at the inlet of PND<sub>1</sub>) and downstream (at the outlet of the VPR).

*Note: It is imperative that the response of these PNCs is verified before the VPR is calibrated; this is to ensure that the two PNCs are equivalent. The upstream and downstream concentrations are directly compared with each other to calculate the particle concentration reduction factor and volatile particle removal efficiency of the VPR; therefore the PNCs must be compared with each other. The secondary calibration method for PNC calibration is recommended, as detailed in the ‘Condensation Particle Counter Calibration Procedures’<sup>3</sup>. The linearity of response in terms of the R<sup>2</sup> coefficient must be greater than 0.97, else the PNCs do not respond linearly over the measured concentration range. If the two PNCs do not meet these requirements the upstream and downstream concentrations may not be directly compared. The PNCs response at all particle sizes and concentration should be compared and measurements taken with one PNC adjusted to align with the other PNC.*

Additionally, care must be taken when comparing the results from two PNCs if they are not the same model, this was particularly important in this example as one PNC had been modified to provide lower size detection limits of  $23\pm 3$  and  $37\pm 4$  nm for 50 % detection efficiency ( $D_{50}$ ) and 90 % detection efficiency ( $D_{90}$ ) respectively than the standard model of TSI PNC 3010. The AEA PNC was unmodified having a  $D_{50}$  of  $9.5\pm 0.5$  nm and  $D_{90}$  of  $13.5\pm 0.5$  nm. Thus significant differences between the concentrations reported by both PNCs would be expected if the calibration particles were smaller than around 40 nm. For the VPR calibrations at 30nm the AEA PNC was used in both the upstream and downstream sampling positions through equivalent sampling lines. The downstream sampling line was exchanged for the upstream sampling line, the number concentration was allowed to stabilise and then the upstream sampling was reconnected to the PNC to verify that the inlet concentration had not drifted throughout the measurements.

Identical flow paths were used to deliver the calibration particles from the electrostatic classifier to the PNCs and the VPR inlet, thus ensuring any losses within the pipe work were the equivalent for all measurements.

For each monodisperse diameter and nominal dilution setting the system was allowed to stabilise for at least 10 minutes before selecting the next setting. When the measurements were complete at each nominal dilution setting the particle diameter was changed. The results were analysed to calculate the particle concentration reduction factor at each nominal dilution setting and the suppression of nucleation particles.

**Add results from the calibration measurement exercise**

## 9 Annex 2: example of particle concentration reduction factors ( $f_r$ )

For VPRs with a variable secondary diluter (PND<sub>2</sub>) Table 2 illustrates the minimum number of particle concentration reduction factors required for primary calibration. For VPRs with a fixed PND<sub>2</sub> dilution setting only the first set of particle concentration reduction factors would be required (highlighted in yellow).

**Table 2: Examples of particle concentration reduction factors ( $f_r$ )**

Primary Diluter Setting (PND <sub>1</sub> )	Secondary Diluter Setting (PND <sub>2</sub> )	Particle concentration reduction factor ( $f_r$ )
1	1	
2	1	
3	1	
4	1	
5	1	
1	2	
2	2	
3	2	
4	2	
5	2	
1	3	
2	3	
3	3	
4	3	
5	3	



