PMP MEASUREMENT SYSTEMS FROM EXIS

Introduction and background

ExIS is proud to be able to offer the most comprehensive selection of instrumentation and equipment for particle number measurement among any distributor of such equipment in Scandinavia. ExIS co-operate with the leading instrument manufacturers in this field, such as: Dekati (FIN), Ecomesure (F), Grimm Aerosol Technik (DE), Matter Aerosol (CH) and Pegasor (FIN).

An overview of the instrumentation and equipment we offer is made in this paper. Additional documentation, such as e.g. brochures, data sheets, technical notes and much more is also listed as references. Note that hyperlinks are extensively used in this paper. These hyperlinks refer to documents on the ExIS internet site that provide more information of specific topics. To enable opening/download of the documents in your web browser, or any other appropriate software, you may have to accept this in the specific software. If you, for some reason, cannot download any of these documents, you can send an e-mail to info@exisab.com and state which document you want to obtain and then we can provide this document to you by some other means.

Background - The PMP programme

Adverse health effects from vehicle particle emissions have become a great concern in the scientific community. Not only particle mass but rather the smallest particles, i.e. ultrafine particles (diameter <100 nm) and nanoparticles (diameter <50 nm) are suspected to cause both short-term (daily mortality and morbidity) and long-term health effects (e.g. cancer and cardiovascular diseases). Emission norms for engines and vehicles in the past have only regulated the particle mass. Particle number is dominated by small particles, but these particles have little contribution to the total mass. The issues above were the main drivers behind the Particle Measurement Programme (PMP), which was initiated by a Working Group of the UN-ECE [1].

The objective of the PMP programme was to develop new particle measurement technologies to complement or replace the existing particulate mass measurement, with special consideration to measuring particle emissions at very low levels. In the PMP programme, it was concluded to measure only solid particle number (SPN), since these are anticipated to have the most adverse health effects. Thus, volatile particles are removed. As the PMP measurement protocol now is being finalised in amendments to current ECE Regulations (ECE Regulations R83 and R49), new measurement systems have been developed to fulfil the criteria set in this regulation [2]. The latest PMP report (available only in draft versions when this document was written) is about the heavy-duty interlaboratory correlation [3, 4]. This report provides...

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1 A lot of software warns for potential virus before you open a file. We can assure you that every file ExIS publish on our Internet site has been checked for virus and any other potential malware.

2 Numbers in bracket refer to a publication that is listed in the reference list at the end of this paper.
further insight not only about measurements on heavy-duty engines but also in general.

In brief, the PMP measurement system may be described as: a sampling probe inside the CVS-tunnel; a unit to remove coarse particles; a dilution unit to provide a dilution factors (DF) in the range of 1:1 to 1:1000; an evaporation tube (ET) to heat the aerosol for volatile material removal; a second dilution stage to provide DF 1:1 to 1:30 and an instrument to measure the particle number concentration. A schematic picture of the PMP setup is shown in the figure below.

The measurement system comprises, among other things, a volatile particle remover (VPR) as one of the most important sub-systems. The VPR has a first hot stage of dilution (PND1) and a second cold stage (PND2) with an evaporation tube (ET) in between these stages. The ET, which must operate at a fixed temperature level between 300ºC and 400ºC, evaporates the potentially remaining volatiles from the hot stage of dilution.

For particle number counting (PNC), an instrument of the condensation particle counter (CPC) type is foreseen. In fact, the ECE Regulations R83 and R49 are written for this type of instrument. It should be noted that other types of instruments also can count the total number of particles but these can so far not be used for legislative purposes (e.g. certification, in-use compliance, and so on...) according to the current legislations. The specification for the CPC is thoroughly set, which has necessitated the development of adapted CPC instruments. Among other things, the lower cut-off diameter is limited to 23 nm, implying that the counting efficiency should be 50% at this diameter and particles smaller than that are practically not counted.

Two different options can be used to remove the largest particles from the exhaust dilution tunnel. One options is a cyclone with a cut-point between 2.5 and 10 µm and the other options is the so-called Chinese hat, a device that has been commonly used in automotive measurements in the past. Note that only one of these options shall be used, not both.
PMP measurement systems offered by ExIS

ExIS can offer two complete PMP measurement systems, one from Ecomesure and one from Matter Aerosol. A complete PMP measurement system shall fulfil all the requirements according to the PMP protocol, and (preferably) in addition, also specific requirements from the automotive industry, such as automated procedures for e.g. zero check, dilution air cleanliness and many other operational functions. Another often desired feature is full integration with the test cell computer. Besides the two systems described below, ExIS can also provide stand-alone dilution systems and particle counters. In some cases, these are also components of complete PMP measurement systems, so to obtain a full picture, the reader is recommended to also study the components of the full measurement systems.

RS-PMP from Ecomesure

The RS-PMP measurement system is produced by Ecomesure; a distributor of Dekati and Grimm products in France. The RS-PMP system was developed in co-operation between Ecomesure, Dekati and ExIS, with support from Grimm regarding CPC development.

The RS-PMP comprises a DEED dilution system (described in more detail below) and a Grimm CPC integrated in a measurement rack with a touch-screen PC-based control system. Instead of the limitation to high/low DR selection, as for the DEED, a mass flow controller provides a wider range of dilution ratios and an extension of the dilution ratio to 1:6 000, according to requirements of the German automotive industry. RS-PMP does not offer infinitely variable dilution ratio but has 6 fixed dilution ratios instead. The lowest dilution ratio is 1:10 (obtained through by-pass of one ejector diluter) and 5 ratios are available within the range of 1:100 to 1:6 000. All the requirements of a fully-integrated PMP measurement system for automatic checks (e.g. zero, leakage, etc.) are fulfilled by the RS-PMP.

The software has been developed for intuitive and simple operation and uses AK protocol for host computer communication. Convenient operation of the unit in test cell environment is enabled via the built-in touch-screen PC.

RS-PMP was first tested at the French official emission laboratory UTAC in spring 2008 with very good results and since then, it has been tested by several automotive companies, automotive suppliers and by independent test institutes. Delivery of the RS-PMP system started in autumn 2008.

Developments of the RS-PMP instrument since the introduction in 2008 has been the adaptation to a smaller rack of only 140 cm (excl. rollers) in height and some internal
hardware modifications. A further reduction in height to 120 cm is also an option if a somewhat smaller touch-screen PC is mounted. An optional by-pass of one of the ejector diluters enables as low dilution ratio as 1:10. This sample is available through a specific outlet in the panel. A low dilution ratio is useful for using other particle instruments than a CPC. At very low emission levels, such instruments normally require much lower dilution ratios than a CPC. Improvements of the RS-PMP software have also been done subsequently to simplify operation and to enable new features.

Besides the improvements mentioned above, all the accessories described below for the DEED dilution system can also be used in conjunction with the RS-PMP measurement system.

Future developments of the RS-PMP will provide real-time mass emission data in addition to particle number emissions.

Further information about the RS-PMP instrument can be found in the [RS-PMP brochure](#).

**The rotating disk diluter from Matter Aerosol**

The rotating disk diluter provided by Matter Aerosol (previously Mater Engineering) of Switzerland was the first commercial measurement system developed for PMP measurements. It was used as the “golden” measurement system in the PMP programme for light-duty vehicles. Thus, it is probably one of the best characterised measurement systems, which has manifested itself in numerous publications.

The rotating disk diluter provides a very wide range of dilution ratios ranging from 1:15 to 1:3 000, where the dilution ratio is infinitely variable. The latest version of the rotating disk diluter, MD19-3E, was introduced in the spring 2009. The target for the new MD19-3E diluter was to achieve a lifetime of 1 000 hours for the diluter head. After testing a broad variety of materials and designs, the new MD19-3E fulfils this target. In addition to the above mentioned modifications, the peristaltic pump was replaced with a rotating pump, which dramatically reduces the maintenance, as there is no more need to change the peristaltic pump tube. The new cyclone is much smaller and does not need an extra pump. The lightweight cyclone also contributes to the reduction of the general size of the diluter head, improving handling, flexibility and ultimately save installation and maintenance costs.

The dilution principle of the full PMP-compliant system, meViPR, is based on the MD19-3E rotating disk diluter described above. The dilution system is a “plug-and-play” system that can be combined with a CPC for an integrated complete PMP measurement system. In the version of the meViPR system provided by ExIS, a CPC from Grimm is used. Remote operation of the meViPR from the test cell computer via the AK protocol can be obtained on request.

Further information about the rotating disk diluter can be found in the latest [MD19-3E datasheet](#).
Components for PMP measurement systems

PMP CPC by Grimm

The PMP protocol sets a couple of requirements for the particle counter. Grimm has developed a special CPC to fulfil these requirements. The Grimm PMP CPC, model 5.412, is based on the well-proven 5.400 series. It includes many specific features first introduced by Grimm, such as, e.g., butanol safety measures (anti-spill and odour removal) that have later been copied by other CPC manufacturers.

The CPC from Grimm can be used as a stand-alone instrument in combination with a dilution system, or as part of an integrated measurement system (see description of the RS-PMP instrument below). In the latter case, a specially developed CPC instrument is provided by Grimm that is slightly different to the stand-alone CPC for automotive applications.

Further information about the automotive CPC from Grimm can be found in the latest Grimm automotive CPC brochure.

Further information about Grimm nano instruments can be found in the latest Grimm general nano catalogue.

Dekati DEED

The modifications in the draft PMP protocol in spring 2007 enabled significant simplifications of the PMP dilution system. These simplifications enable the design of a more accurate and cost-effective dilution system and – last but not least – simplified operation. The Dekati Engine Exhaust Diluter (DEED) was designed with this objective in mind.

No special user training is required to operate the DEED; just switch on, warm up and go! The dilution ratio can be varied in two stages; i.e. high (for high emissions) and low (for low emissions).

DEED is based on the ejector diluter principle, which has no moving parts and has a long record of reliable operation. The Dekati ejector diluter is worldwide the most sold and proven diluter of this kind. Very low losses in the ejector diluter minimize the instrument downtime. Pressure balancing of the diluters eliminates influence of varying CVS (or exhaust pipe) pressure. DEED can be combined with any type of particle instrument. It is mounted in a single rack cabinet and can be controlled remotely via the AK protocol.

Recent development for the DEED dilution system includes hardware and software modifications. In addition, a comprehensive list of accessories has been added. One of the new features is an optional “by-pass” of one of the ejector diluters that provides an
additional outlet of sample gas for a low dilution ratio of 1:10. Some of the specific DEED accessories are:

- DEED-150 post-DPF sampler
- DEED-300 pre-DPF sampler
- DEED-500 PMP compliant cyclone
- DEED-900 AK-protocol software
- FPS-4001 Pressurised air filtration and drying unit

The post-DPF sampler comprises a heated stainless steel sampling line and a probe. For sampling at high pressure and high concentrations (such as before DPF), the pre-DPF sampler comprise a “mini-CVS” device and an additional dilution stage (ejector diluter). The mini-CVS is also available separately (i.e. without the ejector diluter). The FPS-4001 pressurized air filtration unit is a new unit compared to the previous one (same designation). One improvement is better filtration of compressor oil. The new unit is also smaller than the old one.

Further information about the DEED and the accessories can be found in the following documents:

- **DEED brochure**.
- **DEED accessories**
- **DEED-300 pre-DPF sampler**

**Other number-counting particle instruments**

As mentioned above, the CPC type of instrument is foreseen for particle counting in the new EU emission regulations. However, this instrument type has one crucial drawback, i.e. it counts all particles regardless of the particle size (within the lower and upper limitations of the instrument). Another feature of interest for research and development purposes would be to also measure particle mass in real time. Both these shortcomings can be overcome by the alternative instruments discussed below.

This overview is limited to real-time instruments, since the requirements from the motor industry is usually that such instruments should be able to measure under transient conditions.

**ELPI from Dekati**

The principle of the Electrical Low Pressure Impactor (ELPI) was first conceived by Keskinen et al. at the Tampere University of Technology (TUT) in Finland. ELPI was introduced on the market by Dekati in the mid 1990’s as the first instrument that could measure a wide size range of particles in real time conditions. Since then, the ELPI instrument has been continuously developed further.

The ELPI operating principle is based on particle charging and classification in a cascade impactor. The currents from each stage are measured with sensitive electrometers. In the open
literature, there are numerous comparisons between ELPI and CPC instruments that show excellent correlations. Thus, ELPI can be used to provide more insight about e.g. the filtration efficiency of diesel particle filters (DPFs) as function of particle size.

At the International Aerosol Conference (IAC) in Helsinki (August 29 to September 3, 2010), Dekati presented the new ELPI+™ instrument. Though radically new in its design, and with many improvements and new features, the ELPI+ is built on the same principles as the “old” ELPI. The list of new features and advantages of ELPI+ is too long to be included here but some of these of importance for automotive measurements are listed below:

- Increased number of size fractions; now 14 instead of 12 (i.e. 15 impactor stages instead of 13 stages). With a data inversion algorithm, a much larger number of channels can be interpolated and displayed.
- Wider size range: 6 nm to 10 μm
- Improved sensitivity and an increase in maximum concentration
- Significantly faster impactor and charger cleaning with the new impactor and charger design
- 10 Hz sampling rate
- Improved software
- Analogue (6) in an outputs (3)

Further information about the ELPI+ instrument can be found in the ELPI+ brochure. During a transitional period, the “old” ELPI will also be available (ELPI brochure). Supply of spares and support for the old ELPI will continue for many years to come.

DMM-230a from Dekati

The Dekati Mass Monitor (DMM) was developed to provide data on real-time particle mass emissions in the exhaust from diesel and petrol engines. The operating principle is similar to the well-proven ELPI instrument, with the addition of a mobility channel that provides data for calculation of the effective particle density that is used for determination of particle mass emissions. Important factors such as, ease of use, robustness and reliability have been considered in the development of the DMM instrument. The latest version of the instrument, i.e. the DMM-230a, was introduced in the autumn 2008 (see description below).

Despite the discussed number-based measurement standards, the mass emission is still used in all regulatory measurements. Conventional PM measurements are based on
gravimetric filter weighing, resulting only in a total, cumulative mass emission. Real-time data from DMM provides second-by-second (1 Hz) information about particle total mass during accelerations, decelerations and different speed points immediately during the measurement. This is of particular interest in, e.g. determining DPF loading and development of regeneration strategies. DMM also provide information about the size distribution (mass median size and geometric standard deviation). With a detection limit below 1 µg/m³, DMM provides about one order of magnitude better resolution than competing instruments in this field. Furthermore, DMM measures not only soot but all particles. Preferably, volatile particles can be removed in the dilution process to mimic the PMP sampling conditions for particle measurement, as described above.

The latest development of the DMM instrument hardware (DMM-230a) includes sheath air for the charger, which enables longer intervals of operating time between cleaning. The latest software also provides total particle number emissions similar to the PMP protocol. These features were introduced in the autumn 2008. Thus, DMM is now a “complete” instrument providing results on particle mass, total number and size distribution. New for 2009 is communication with the host computer in the test cell via the AK protocol. Upgrades of current units in operation to the DMM-230a hardware can be provided on request.

Further information about the DMM instrument can be found in the DMM brochure.

The meDisc from Matter Aerosol

The meDisc is a new instrument from Matter Aerosol. It is based on the same principle as a diffusion battery but with some additional innovations. The aerosol sample is charged and passes through 3 measurement stages. In the diffusion stage, the smaller particles are deposited at a series of stainless steel grids. After that, the aerosol passes through an induction stage and finally they are deposited on a filter. Sensitive current amplifiers measure the current from the mentioned stages. A calculation of particle number and size (20 to 200 nm interval) is made. Among the features of the meDisc instrument are that it is portable, robust and easy to use.

New on-going development for the meDisc includes the integration of a rotating disk dilution system to provide a portable measurement system (PEMS) for on-board measurement of particle number emissions. Although not compliant with the PMP protocol, this measurement system provides a very cost-effective and convenient solution for on-board measurements of particle number emissions.

The technology from meDisc will also be used in the NanoMetIII, a portable instrument under development for measuring particles in engine exhaust. The meDisc is combined with a raw gas diluter and a thermodiluter to enable a VPR according to the R83 Regulation. More details on this instrument will be provided later.

Read more about meDisc in the meDisc brochure.
FAPES from Grimm

The FAPES instrument from Grimm is based on the technology of using a battery of 10 Differential Mobility Analyzers (DMA) in combination with Faraday Cup Electrometers (FCE). Thus, very high sensitivity and time resolution can be provided. FAPES has the highest “true” time sensitivity of all types of instruments that can provide real-time size distributions. The internal data rate is 100 Hz and size distribution data can be provided up to 10 Hz. Through the use of a data inversion algorithm, size distribution of 21 channels can be provided. Due to the use of sheath air, the DMAs and FCEs are insensitive to fouling and thus, require very little maintenance.

A dedicated dilution system can also be included with the FAPES instrument.

Read more about FAPES in the FAPES brochure.

PPS-M from Pegasor

The novel Pegasor Particle Sensor (PPS) was launched for production in March 2010. PPS measure particles directly in raw exhaust and thus, it need no external sampling and dilution. At a sampling rate of up to 100 Hz, PPS provides exceptional time response. Since no external dilution is needed, the time delay and signal smoothing of such devices can be avoided.

PPS operates by electrostatic charging of particles passing through the sensor and then measuring the current caused by the charged particles leaving the sensor. The flow-through design keeps the sensor clean for extended operation and low maintenance. The particle charger is only exposed to clean air. PPS is generally characterized by its simplicity and robustness. Thus, it is well-suited for on-board measurements and is also used as such in the Micro-PSS measurement system by our Italian partner Control Sistem.

For automotive applications, the PPS-M is calibrated for both particle number and particle mass. Thus, PPS-M can provide a low-cost alternative to other particle number measuring devices. In the general setup, PPS-M measures all kind of particles regardless of particle composition. However, since sampling is made at high temperature, only solid particles will be measured under normal “hot” conditions. In cases where sampling conditions are different, a heated sampling line can be used for volatile particle removal similar to the requirements in PMP. PPS-M is available in high-sensitivity and high-concentration versions as well as low and high-temperature versions.

Read more about PPS-M in the PPS-M brochure.
PMP type and PMP like dilution systems

In the latest PMP report on heavy-duty engines, a nomenclature for various types of PMP sampling and diluting was introduced [4].

- PMP type systems
- PMP like systems

“PMP type” systems operated according to the principles specified in R83 and R49. The stand-alone versions of the rotating disk diluter and the Dekati double diluter system with an evaporation tube are two such examples.

The definition of “PMP like” by the authors of the mentioned report is somewhat vague. A number of “different concepts for the dilution and thermal treatment” were tested. In our (ExIS) simple definition, a PMP like system should provide a VPR function similar to a PMP type system. Furthermore, it is advantageous that the particle losses are low or at least compensated for. In other words, a PMP like system should be able to give same results as a PMP type system.

Double diluter upgrade

The Dekati double diluter system with an evaporation tube was classified as a PMP type in the heavy-duty PMP report [3,4]. The fully PMP compliant DEED from Dekati is also based on a double ejector diluter. This type of ejector diluter is the most sold of its kind in the world. Therefore, we have noted that many customers ask for an evaporation tube as an “upgrade” for their double diluter system. This is now available as a separate component. A heater controller for the evaporation tube is also needed. In practice, a double diluter system with an evaporation tube is equivalent to DEED in its ability to function as a VPR but, of course, it lacks some of the features of the more sophisticated DEED system. Note that to meet the requirements for PMP sampling, the dilution air cleaning must be sufficient. A dilution air cleaning system that fulfils the PMP requirements can also be offered.

To qualify as a PMP type system according to the mentioned PMP report, the double diluter system with an evaporation tube should sample from a CVS tunnel [3, 4]. There are also other options to use a double diluter system, e.g. to sample directly from the exhaust pipe, as the customized solution by EMPA that was tested in the mentioned report. This system was classified as a PMP like system. Dekati provide a couple of accessories for tailpipe and pre-DPF sampling that can be used in this case. Instead of an evaporation tube, a Thermodenuder could also be used (see further comments below). Note that ejector diluters used for raw exhaust sampling must be “pressure balanced” to avoid impact from varying pressure, i.e. the outlet pipes with “exhaust” from the ejectors must be connected back to the tailpipe slightly downstream of the sampling point. The impact of varying temperature on the dilution ratio must also be considered. Measurement of temperature at diluter inlet and using a correction algorithm is one option. Another option is to use a heated sampling line that will give a constant temperature and therefor a constant correction factor.

Read more about the ejector diluter in the Diluter brochure. More information sampling and setup of ejector diluters is provided in the Diluter Technical Note.
**FPS**

The Dekati FPS-4000 is a comprehensive and flexible dilution system for a variety of different applications. As such, it can also be used as a PMP sampling system. The FPS was not tested in the latest heavy-duty PMP report, so it has not been classified as a PMP type or a PMP like system.

An evaporation tube can be used as an accessory to FPS to enable the VPR function. A Thermodenuder can also be used with the same purpose. The Dekati Thermodenuder has been characterized for particle losses, so a compensation for these losses can be made. The losses are within the limits in the PMP requirements. The FPS already has a built-in temperature controller that can be used for an evaporation tube or a Thermodenuder, so no additional investments are needed for that purpose. It is likely that an FPS system with an evaporation tube would be classified as a PMP type system and as a PMP like system with a Thermodenuder, when sampling is made from a CVS in both cases. In case sampling is made directly in tailpipe, the FPS would be a PMP like system. FPS already has built-in calculation of the impact of temperature and pressure on dilution ratio, so no compensation has to be made in this case for tailpipe sampling, as for the ejector diluters mentioned above.

Read more about FPS in the [FPS brochure](#) and about the Thermodenuder in the [Thermodenuder brochure](#).

**Dilution for other instruments than a CPC**

The PMP sampling and conditioning system was intended to be used with a CPC. The CPC type of instrument has very high measurement resolution but cannot measure at high concentrations. Furthermore, a CPC does not provide any information about particle size distribution. These shortcomings are obvious for research and development applications, where more information than just total particle number is of interest. At the same time, the PMP dilution is intended for high or very high dilution ratios, which implies that these dilution systems are not ideal for such applications.

For instruments that can characterize particle size or measure particle mass in real time, the dilution ratio should be kept relatively low compared to the dilution for a CPC (i.e. ultimately as low as 1:10 – or lower – when connected to a CVS tunnel), so that the concentrations can be maintained at a level suitable for such instruments. However, for these applications, a “PMP-like” dilution system is still desired, either for tailpipe sampling or for mounting directly on a CVS tunnel. With the FPS dilution system – potentially using additional accessories in some cases – this can be accomplished relatively easily. Therefore, this is not discussed further here. Instead, a couple of options using an ejector diluter and accessories for the DEED dilution system are described.

The alternative dilution systems described below can provide similar result as the PMP dilution regarding volatile particle removal of but often with far less complexity and
thus, they are also much more cost-effective than fully PMP-compliant dilution systems.

A large collection of accessories to the DEED dilution system is available. The PMP like systems discussed below are either based on the DEED-100 or a combination of the accessories for DEED. Some of these accessories are described below:

- DEED-150c, for post-DPF sampler
- DEED-300, for pre-DPF sampler
- DEED-500, PMP compliant cyclone
- Thermodenuder for VPR
- FPS-4001, pressurised air filtration and drying unit (note: new version)

A more thorough description of the components listed above is provided in a separate document (see end of this section) but a quick overview is provided here.

**DEED-150c** is a 3 m flexible stainless steel heated sampling line (optionally 0.5 m incremental lengths up to 8.5 m are available) and a probe for sampling in raw exhaust, e.g. after a DPF. Heating is controlled by the DEED-100 or via a separate control unit.

**DEED-300** is a sampler for sampling in raw exhaust at high overpressure, e.g. before a DPF. A minimum overpressure of 30 mbar is necessary for satisfactory operation. DEED-300 comprise a “Mini-CVS” diluter based on the Dekati axial diluter (DAD) and an ejector diluter (DI-1000). The total dilution ratio is about 40:1 (individually calibrated). The excess sample from the Mini-CVS is “dumped” via a hose to local exhaust. Due to the innovative design, the DEED-300 always keeps a constant total dilution ratio regardless of pressure and temperature conditions inside the tailpipe.

**DEED-500**: The PMP protocol provides two options to use either a cyclone or a so-called Chines hat to prevent large particles to enter the system. DEED-500 is a PMP compliant cyclone that directly fits the DEED-100.

The Dekati Thermodenuder is a device used in many different applications and some of them are discussed below. The Thermodenuder removes volatiles via heating and adsorption in cartridges of activated carbon. It has certain particle losses but these losses have been characterized and can be corrected for. To limit the use of consumables (activated carbon), a Thermodenuder is best suited for diluted gas and/or low HC concentrations. This is taken into account in our recommendations below.

**FPS-4001**: Very clean dilution air is needed for PMP dilution. FPS-4001 is a new version of the pressurised air filtration and drying unit that comprise a coarse filter, a HEPA filter, an oil mist filter and maintenance-free dryer using Nafion® membranes. FPS-4001 fulfils the requirements in the PMP protocol.

A couple of different setups using the DEED-100 and the use of various accessories are described in the Dekati application note about PMP sampling (see link below). However, some options are not included in that document. An overview of the various setups is provided below. Schematic setups for the following three different cases are shown:
1. PMP like sampling in a CVS tunnel
2. PMP like sampling in the tailpipe after the DPF
3. PMP like sampling in the tailpipe before the DPF

The options for sampling from the CVS tunnel are shown in Figure 1. DEED-100 and a heated sampling line (DEED-150c) as option is used in the standard case unless the concentrations are extremely low, as when a DPF is fitted on the engine. The heated sampling line can be used to reduce thermophoretic losses and is controlled at a temperature of ~60°C. At very low concentrations, a heated sampling line can be used as an evaporation tube (controlled at ~350°C in this case) in combination with an ejector diluter (DI-1000) to cool the sample down to ambient temperature. A Thermodenuder with an ejector diluter is in principle an equivalent solution. At extremely low concentrations, the ejector diluter can be omitted in the last case.

Figure 1. PMP like sampling in a CVS tunnel

In Figure 2, sampling after a DPF is shown. In this case, DEED-100 is best suited for a CPC, since the concentrations are anticipated to be very low and the dilution ratio with DEED-100 is likely to be too high for other instruments than a CPC. The heated sampling line (~60°C) can be used here as an option to reduce the thermophoretic losses as described for the previous setup. Both alternatives that us a heated sampling line as an evaporation tube (controlled at ~350°C) and Thermodenuder respectively are viable options also for this setup case as in the previous setup (in Figure 1). Potentially, the ejector diluter could be omitted also here at very low concentrations in the combination with a Thermodenuder.
Figure 2. PMP like sampling in the tailpipe after the DPF

In Figure 3, a setup for sampling before the DPF is shown. DEED-100 is used here in combination with the equipment for sampling before DPF (DEED-300). The heated sampling line can be used here as an option to reduce thermophoretic losses and is then regulated at ~60°C. Dilution ratios suitable for both CPCs and other instruments, such as, e.g. ELPI, can be obtained using the mentioned setup. For lower concentrations, the components in DEED-300 are “separated” and a heated sampling line is used as an evaporation tube (controlled at ~350°C) and then the sample is cooled in the ejector diluter. A third option that comprises a Thermodenuder is conceivable also here but is not shown in Figure 3. The rationale for not using the Thermodenuder in this case is that the sampling is made before the aftertreatment with significantly higher hydrocarbon concentrations than after catalytic aftertreatment. Thus, the consumption of activated carbon cartridges would be higher. One possible setup would be to use DEED-300, which provide a total dilution ratio of 40:1, in combination with a Thermodenuder to reduce the HC concentration. A higher dilution ratio reduces the need for consumables.
Above, a couple of examples using readily available components to achieve PMP like sampling at low dilution ratios were described. However, there are also other options and we realize that there are applications when further customization might be necessary. Contact us for more information about how to customize a solution for your particular measurement application.

Further information about the DEED, the accessories and some of the setup options can be found in the following documents:

- **DEED brochure**
- **DEED accessories**
- **DEED-300 pre-DPF sampler**
- **Dekati solutions for PMP sample conditioning**

### Summary and conclusions

In the introduction of this paper, it was boldly stated that ExIS can offer the most comprehensive selection of products for measurement of particle number. The examples provided in this paper should prove this point beyond doubt. The only reservation is that we have limited ourselves to compare us with suppliers of such equipment on our market, i.e. Scandinavia.

Until now, the focus of the industry has mostly been on instrumentation for measuring according to the PMP protocol. This is of logical because this protocol will be used for engine/vehicle certification. Consequently, this has also attracted the interest from large suppliers of test equipment for the mentioned industry, such as AVL and Horiba. Although ExIS are also in the position to supply fully-compliant PMP instruments,
such as the RS-PMP and the rotating disk diluter, our focus is mostly on instruments for research and development purposes. Particle counters as CPCs are relatively “crude” instruments that provide relative little information. They give only total number and the time resolution is relatively poor. Instruments that can provide information about particle size, mass, charge and other properties, as well as fractionating and collection of those particles for later chemical analysis offer additional insight about the emissions from an engine. Furthermore, it can be noted that also an improved time resolution is of great importance. In that respect, we refer to “true” good time response, as we can obtain with PPS-M, FAPES and ELPI+.

In many of the application cases we have made for customers, we also need to provide our own expertise and the expertise from our partners to suggest solutions and solve problems associated with these measurement applications. Also in this field, we can provide comprehensive experience from aerosol measurements in automotive applications. Note that support on phone and e-mail is available free of charge; a service that not all suppliers are willing to offer.
References and further reading


2. Draft versions of the Regulations are available at the Internet site of the UN-ECE via the links below, accessed in August 2010.


5. The English RS-PMP brochure is available at the Internet site of ExIS at: www.exisab.com or directly via this link: RS-PMP brochure.

6. Datasheet for the MD19-3E rotating disk diluter is available at the Internet site of Matter Aerosol (www.matter-engineering.com), ExIS (www.exisab.com) or directly via this link: MD19-3E datasheet.

7. Brochures for the Grimm CPCs are available at the Internet site of Grimm (www.grimm-aerosol.com), ExIS (www.exisab.com) or directly via these links: Grimm automotive CPC brochure and Grimm general nano catalogue.

8. Information about DEED is available at the Internet site of Dekati (www.dekati.com), ExIS (www.exisab.com) or directly via these links: DEED brochure, DEED accessories and DEED-300 pre-DPF sampler.

9. Information about ELPI is available at the Internet site of Dekati (www.dekati.com), ExIS (www.exisab.com) or directly via this link: ELPI brochure.

10. Information about DMM is available at the Internet site of Dekati (www.dekati.com), ExIS (www.exisab.com) or directly via this link: DMM brochure.

11. The meDisc brochure is available at the at the Internet site of Matter Aerosol (www.matter-engineering.com), ExIS (www.exisab.com) or directly via this link: meDisc brochure.
12. The FAPES brochure is available at the at the Internet site of Grimm (www.grimm-aerosol.com), ExIS (www.exisab.com) or directly via this link: [FAPES brochure](#).

13. Information about PPS-M is available at the Internet site of Pegasor (www.pegasor.fi), ExIS (www.exisab.com) or directly via this link: [PPS-M brochure](#).

14. Information about the Dekati Diluter and the setup for automotive sampling is available at the Internet site of Dekati (www.dekati.com), ExIS (www.exisab.com) or directly via these links: [Diluter brochure](#) and [Diluter Technical Note](#).

15. Information about the FPS and the Thermodenuder is available at the Internet site of Dekati (www.dekati.com), ExIS (www.exisab.com) or directly via these links: [FPS brochure](#) and [Thermodenuder brochure](#).

16. Information about PMP like sampling is available at the Internet site of Dekati (www.dekati.com), ExIS (www.exisab.com) or directly via this link: [Dekati solutions for PMP sample conditioning](#).
### Abbreviations, acronyms and glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BC</td>
<td>Black carbon or insoluble carbon</td>
</tr>
<tr>
<td>BS</td>
<td>Black Smoke</td>
</tr>
<tr>
<td>CNC</td>
<td>Condensation Nuclei Counter (equivalent to CPC)</td>
</tr>
<tr>
<td>CPC</td>
<td>Condensation Particle Counter (equivalent to CNC)</td>
</tr>
<tr>
<td>CVS</td>
<td>Constant Volume Sampler/Sampling, a dilution device used for dilution of engine/vehicle exhaust for emission measurements.</td>
</tr>
<tr>
<td>DI</td>
<td>Direct Injection</td>
</tr>
<tr>
<td>DISI</td>
<td>Direct Injection Spark Ignition</td>
</tr>
<tr>
<td>DMA</td>
<td>Differential Mobility Analyzer</td>
</tr>
<tr>
<td>DMM</td>
<td>Dekati Mass Monitor, an instrument (Dekati Ltd. in Finland) for measuring (indirectly) particle mass in real time</td>
</tr>
<tr>
<td>DMPS</td>
<td>Differential Mobility Particle Sizer</td>
</tr>
<tr>
<td>DPF</td>
<td>Diesel Particle Filter</td>
</tr>
<tr>
<td>DR</td>
<td>Dilution Ratio</td>
</tr>
<tr>
<td>EC</td>
<td>Elemental carbon</td>
</tr>
<tr>
<td>EEPS</td>
<td>Engine Exhaust Particle Sizer, an instrument (TSI Inc.) that measures particle number and particle size distribution in real time</td>
</tr>
<tr>
<td>EEV</td>
<td>Enhanced Environmentally Friendly Vehicle</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
</tr>
<tr>
<td>ELPI</td>
<td>Electrical Low Pressure Impactor, an instrument (Dekati Ltd. in Finland) that measures particle number and particle size distribution in real time</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency (USA)</td>
</tr>
<tr>
<td>ESC</td>
<td>European Stationary Cycle</td>
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<tr>
<td>ETC</td>
<td>European Transient Cycle</td>
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<tr>
<td>EUCAR</td>
<td>European Council for Automotive R&amp;D, the automotive manufacturer’s association for research and development in Europe</td>
</tr>
<tr>
<td>EUxDC</td>
<td>Extra Urban Driving Cycle</td>
</tr>
<tr>
<td>HD</td>
<td>Heavy-Duty</td>
</tr>
<tr>
<td>HDE</td>
<td>Heavy-Duty Engine</td>
</tr>
<tr>
<td>HDV</td>
<td>Heavy-Duty Vehicle</td>
</tr>
<tr>
<td>IDI</td>
<td>Indirect injection</td>
</tr>
<tr>
<td>IOF</td>
<td>Insoluble Organic Fraction</td>
</tr>
<tr>
<td>JRC</td>
<td>The Joint Research Centre, a research based policy support organisation and an integral part of the European Commission.</td>
</tr>
<tr>
<td>LD</td>
<td>Light-duty</td>
</tr>
<tr>
<td>Nanoparticle</td>
<td>A particle smaller than 50 nm. Slightly different definitions (of size) are also used.</td>
</tr>
<tr>
<td>NEDC</td>
<td>New European Driving Cycle</td>
</tr>
<tr>
<td>OBD</td>
<td>On-Board Diagnostics system</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>PMP</td>
<td>Particulate Measurement Program (the EU programme for developing new measurement methods for particle mass and number)</td>
</tr>
<tr>
<td>PNC</td>
<td>Particle Number Counter. Normally, this refers to a CPC (see above) but this</td>
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abbreviation is actually relevant for any type of particle counter.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction, a NO\textsubscript{X} reducing catalyst</td>
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<tr>
<td>SiC</td>
<td>Silicon Carbide, a common material for monoliths to diesel particle filters (DPFs)</td>
</tr>
<tr>
<td>SIF</td>
<td>Soluble Inorganic Fraction</td>
</tr>
<tr>
<td>SMPS</td>
<td>Scanning Mobility Particle Sizer</td>
</tr>
<tr>
<td>SOF</td>
<td>Soluble Organic Fraction</td>
</tr>
<tr>
<td>SPN</td>
<td>Solid Particle Number according to the PMP (see above) definition. Solid particles remain after passing through a VPR (see below) that has been used to remove volatile particles.</td>
</tr>
<tr>
<td>TD</td>
<td>Thermodenuder, a device that removes volatile aerosols and volatiles adsorbed on solid particles.</td>
</tr>
<tr>
<td>TDI</td>
<td>Turbo Direct Injection, the denotation by VW group for a direct injection diesel engine with a turbocharger.</td>
</tr>
<tr>
<td>TEOM</td>
<td>Tapered Element Oscillating Microbalance, an instrument (Rupprecht &amp; Pataschnik) for measuring particle mass in real time</td>
</tr>
<tr>
<td>TPN</td>
<td>Total Particle Number. All particles that can be counted regardless of composition.</td>
</tr>
<tr>
<td>TWC</td>
<td>Three Way Catalyst</td>
</tr>
<tr>
<td>UDC</td>
<td>Urban Driving Cycle</td>
</tr>
<tr>
<td>UN-ECE</td>
<td>United Nations Economic Commission for Europe</td>
</tr>
<tr>
<td>VOF</td>
<td>Volatile Organic Fraction</td>
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