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Video Exposure Monitoring as Part of a Strategy to Assess Exposure to Nanoparticles

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Objectives: There is a growing awareness of the potential risks for human health of exposure to ultrafine particles or nanoparticles. In that context, workplace air measurements become important, and various strategies have been developed to monitor exposure. In addition, observations and time/activity registrations are part of the exposure assessment strategy in many studies. Video exposure monitoring (VEM) can be of added value in these strategies. VEM combines exposure data with simultaneous video pictures of the process.

Methods: The PIMEX method (Picture Mix Exposure) was used as the VEM studied. The possibility to combine PIMEX and measurement instruments for nanoparticles was the object of this study. The starting point was a review of available instruments for workplace air measurements of nanoparticles. Publications of strategies to assess exposure to nanoparticles were also studied to review whether observations were part of these strategies. Finally, a technical review of combining PIMEX and the compatible measurement instruments was undertaken and explored as part of the strategy to assess exposure to nanoparticles.

Results: A variety of instruments are used to measure nanoparticles. One category is (near) real-time monitoring instruments, which determine numbers and particle size distribution or surface area concentration. Other instruments require sample collection in order to characterize the nanoparticles chemically and physically by microscopic analyses and/or elemental analyses. Only some of these instruments are technically compatible with PIMEX.

With the PIMEX2008 version 1.02 software, it is possible to synchronize up to four different measuring instruments simultaneously with the video recording.

Conclusions: PIMEX as a VEM method can be a useful tool as part of the strategy to assess exposure to nanoparticles. It can also be of value for other purposes like training, education, and risk communication. The possibility to synchronize more than one measuring instrument can be useful to simultaneously monitor different targets in the workplace, e.g. worker exposure in the breathing zone and background concentration.

Keywords: exposure assessment; nanoparticles; ultrafines; video exposure monitoring

INTRODUCTION

The use of nanoparticles has grown tremendously over the last few years. Nanoparticles are defined as particles that have at least one dimension in the nanometric scale, with a size up to 100 nm. Nowadays, it is possible to intentionally manufacture nanoparticles for their specific properties. Nanotechnology influences virtually all industrial and public sectors, including transport, healthcare, and agriculture and is being used in products such as textiles, cosmetics, and medicine. Both the potential benefits and the risks associated with the application of nanoparticles have been widely debated in recent years. At the moment,

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the possible health risks of nanoparticles are not yet fully characterized. There is increasing evidence that potential risks are related to specific properties of nanoscale materials. In this regard, the knowledge of physical and chemical properties such as particle size distribution, morphology, particle composition, particle surface area, particle number concentration, surface chemistry, and particle reactivity in solution are particularly important for the purpose of risk assessment.

Various strategies have been developed to monitor exposure, but so far, no definite standardized international method is available. In addition, there is no application available that is able to measure all relevant exposure parameters simultaneously.

Given the fact that gaps in current knowledge regarding the risks can be expected to continue for some time, it is an obvious step to take precautionary measures.

Internationally, several handling guidelines describing possible risk management activities and best practice have been published (BASF, 2010). These are mainly based on technical feasibility and some of them recommend, based on the precautionary principle, to minimize exposure as far as possible.

Also in the Netherlands, an investigation was carried out to obtain an overview of the current best practices, later redefined into good uses of nanoparticles (Borm *et al.*, 2009). The report also described the associated occupational hygiene measures, handling instructions, communication in the economic chain, and the disposal of nanoparticle-containing waste. Based on the conclusions of this research and based on many other investigations, it is clear that the use of nanomaterials is widespread. There is a growing awareness of the potential risks for human health of exposure to ultrafine or nanoparticles. But most users and producers have little know-how on the methods that can be used to detect the presence of nanoparticles in products or in the workplace environment. Furthermore, the validation of the risk assessment is often lacking. In almost 80% of all interviewed companies, the risk assessment was not supported by any exposure measurements (Borm *et al.*, 2009).

Because of the uncertainty of risks related to the use of nanoparticles, the Dutch Ministry of Social Affairs and Employment (2009) decided to apply the precautionary principle, forcing employers to minimize or even to prevent all exposure of their workers to manufactured nanoparticles. The precautionary principle or safety principle assumes the idea of handling all nanomaterials as toxic substances. In the Netherlands, a good-use-decision-tree was published with a stepwise approach of the risk characterization (Fig. 1).

Fig. 1. The Dutch good-use-decision-tree for the risk assessment of manufactured nanoparticles.

Also several international bodies [NanoSafe, NIOSH (National Institute for Occupational Safety and Health), Health Service Executive, British Standards Institute, and Bundesanstalt für Arbeitsschutz und Arbeitsmedizin/Verband der Chemischen Industrie] have published similar guidelines.

With step 5 'exposure measurements' forming part of the good-use-decision-tree, workplace air measurements become important and the current amount of measurements needs to be intensified. Researchers explored various strategies to monitor workplace air concentrations (Brouwer, 2010) but no definite international harmonized method is yet available. Practical approaches for a tiered approach in view of risk assessment and risk management have been presented. NIOSH presented the nanoparticle emission technique approach (Methner *et al.*, 2010) to semi-quantitatively evaluate airborne particle concentrations. It includes emission source identification and particle concentration measurements using a condensation particle counter (CPC) and an optical particle counter (OPC) aligned with personal air sampling to collect aerosols for off-line characterization. A further tier will comprise a more in-depth evaluation including characterization of particle size distributions.

The BSI (2010) also proposed a multi-step approach where a basic assessment includes determination of source emission by CPC, OPC, and sampling for off-line characterization. A detailed assessment would focus on more specific breathing zone exposure assessment. BASF suggested a similar approach; however, the first tier comprises only particle number concentration. A clear decision logic was developed for entering further tiers (BASF, 2010).

Major methodological issues with respect to a measurement strategy for nanoparticles are still under debate. For example, the (health relevant) metric, distinction from background (ambient and workplace) aerosols, and location of sampling, e.g. source, breathing zone, near field, or far field, are all areas for review. In addition, observations and time/activity registrations are a key part of the exposure assessment strategy. Presently, this is mostly done by observations at the workplace, i.e. watching and registering what is happening. Observation by video recording is not common practice for nanoparticle exposure measurements, whereas it is already used for assessing exposure of certain chemicals (Rosén *et al.*, 2005).

Based on the outcome of Borm's (2009) survey and the overview of the current best practices, the Dutch government stated that visualization of these good practices would provide an increase in knowledge and risk awareness on hazards to nanoparticle exposure. In the last few years, the government gained experience with a visualization technique, called PIMEX, which is a so-called video exposure monitoring (VEM) technique.

VEM is a group of methods used for occupational hygiene studies. The method is based on a combined use of video recordings with measurements taken simultaneously with real-time monitoring instruments. PIMEX, standing for Picture Mix Exposure, was originally developed in the 80s in Sweden by the National Institute for Working Life (Rosén and Lundström, 1987). Similar developments took place around the same time in the USA (NIOSH) under the name VEM (Mc Glothlin, 2005).

Visualization tools contribute significantly in motivating workers and other parties to actively improve working conditions by explaining the hazards of exposure to people of different backgrounds and levels of education (Rosén and Andersson, 2009). Also in the field of nanoparticle exposure, the recorded material of working scenarios and the outcome of nanomonitoring may be used as a risk communication tool in training and education.

Like other visualization tools, there are some aspects to consider. Data visualization tools present information primarily through images rather than words. It also includes any graphic representation of data. An image should ideally be able to convey at least its basic meaning without relying on language. Graphics are often used to convey information about how several variables are related or compared. Presenting data in a visual format can enhance the understanding of people and interest in the data (U.S. Environmental Protection Agency [USEPA], 2002). Nevertheless, data visualization tools may have some shortcomings, for instance, the audience may consider that the information is not complete, the preparation of the information may be time consuming, the audience may not rely on what is presented, and the construction of images may be expensive (Gardner and Stern, 2002).

USEPA has made some recommendations regarding visualization tools: When using, minimize the use of lengthy text and use language that is appropriate for your audience (tailor made information). Furthermore, make use of universal colors and images whenever possible. Some color schemes and images are almost universally recognized, such as red for 'stop', green for 'go', and yellow for 'caution'. The visualization tool should also include actions that people can take to minimize the risk that it is being communicated.

In 2004, PIMEX was introduced in the Netherlands and applied to a range of purposes (Dutch Ministry of Social Affairs and Employment 2007). Commissioned by the Dutch government, Arbo Unie has produced over 100 PIMEX movies freely available through the VASt program, with the aim to implement the existing regulations for hazardous substances in small and medium enterprises. The videos demonstrated through visual action good practices for reducing exposure risks. The good practices were highlighted in green, whereas the 'do nots' were shown in red. Most of the videos were accompanied by voice over with text suitable for factory workers and operators in the industrial environment.

An evaluation study of this VASt program concluded that PIMEX is an effective instrument to help companies to implement the existing regulations on working conditions. At industry level, the effectiveness of PIMEX is greatly appreciated. The visual character of the system has much more persuasive power with both employer and employee. This was seen as a key fact at branch level (Dutch Ministry of Social Affairs and Employment, 2008).

Worldwide, only a few studies have used VEM in combination with nanoparticles, but not as part of a strategy to assess exposure.

The VECTOR project used real-time video monitoring to visualize exposure of cyclists to traffic-related (ultra-) fine particles (Terwoert, 2009). As exposure parameters, the total particle counts within the PM2.5 fraction as well as the PM2.5 mass concentration were determined by using the measuring systems TSI CPC 3007-2 and the DusTrak aerosol monitor. The focus in this project was on the external factors that determine total particle loads, i.e. the specific traffic situations, and not on an exact assessment of, e.g. internal exposure. Although measuring was not only on the nanoscale, with the use of the VEM instructive video clips provided, it was clearly demonstrated which traffic situations are favorable or unfavorable with respect to the exposure to fine particles.

Saamanen *et al.* (2009) tested the use of VEM techniques in locating work activities associated with nanoparticles. This study also utilized two measurement instruments, but both for making near-field concentration measurements only.

In 2009, the Dutch Ministry of Social Affairs and Employment funded a new project. The aim of this study was to determine whether VEM can be of added value in measuring strategies for the exposure assessment of nanoparticles at the workplace. The main elements were review of available instruments that fulfill the technical requirements for combination with VEM, testing VEM in practice, review of main characteristics of internationally published strategies to assess exposure to nanoparticles, and determining possible added value of VEM, especially PIMEX as a good fit to these strategies.

METHODS

In the survey, the availability of measuring instruments was studied as well as the technical requirements for combination with VEM. The PIMEX method was used as the VEM technique.

The PIMEX set is coupled with measurement equipment, a computer, and a video camera. The work situation or activity is filmed and simultaneously real-time measurements are performed (Fig. 2).

The devices are connected to a laptop with PIMEX software. The measurement data are sent to the laptop and integrated with the video so that both the work situation and measurement data are displayed on the screen. Previous versions of PIMEX (PIMEX PC-w and PIMEX-PC-r software) could only allow one direct reading instrument to be connected. With the latest version (PIMEX-2008), up to four different devices can be connected to simultaneously monitor and display exposure.

The range of available instruments for workplace air measurements of nanoparticles were reviewed and compared with the technical requirements for compatibility with PIMEX. After selection of instruments that fulfill these requirements, the technical performance of coupling PIMEX with those instruments was tested. Videoing and monitoring of nano-exposure were tested in practice and PIMEX videos were made. Also publications of methods to assess

Fig. 2. Example of a PIMEX screen. The video picture window shows a person filling cans with acetone and carrying a monitoring instrument for solvents. The graph window shows how the operator's exposure to acetone has varied during the period. The gray bar to the left shows the current exposure level, which is very high.

exposure to nanoparticles were studied to review the characteristics of these strategies. Lastly through practical testing, the added value of the measuring strategies was determined.

RESULTS

Measuring instruments for nanoparticles

The review of available instruments found that there are numerous nanoparticle measuring devices presently available. They can be categorized according to their measuring principle.

The first category comprises the near real-time monitoring instruments which determine (size fractionated) numbers or surface area concentration. Examples are the CPC and scanning mobility particle sizer which determines particle size distribution. An example of the surface area concentration monitor is the diffusion charger manufactured by Matter Engineering AG, called LQ1-DC or electrical aerosol detector).

The second category regards instruments for characterization of nanoparticles. Most of them collect samples in order to characterize off-line the nanoparticles chemically and physically by microscopic analysis and/or elemental analysis.

Because the PIMEX method handles the combination of measuring instruments together with a video camera, both connected to a laptop, there are some technical requirements to the equipment. First, the measuring instruments need to have an analogue output. Nowadays, fewer instruments have analogue output; most instruments have an internal data logging system for analyzing afterwards. Second, the instruments need to be direct reading in order to synchronize with the video. A mean value over a period of minutes is of less value because the exact concentration cannot be evaluated by observation of the actions that take place. A time resolution of 1–3 s would be optimal.

Furthermore, the instrument must ideally be portable for use by operators in the workplaces. Many instruments that currently monitor continuously can only be used for environmental sampling or background sampling because of their weight. Finally, in order to measure inhalation exposure, instruments also need to be personal, so operators can wear them on their body or measurements performed in such a way to measure in the target breathing zone.

By detailed review of the technical information of all the instruments, it was concluded which of these instruments are technically compatible with PIMEX (Table 1).

PIMEX and nanotested in practice

As shown in Table 1, only some of the reviewed measurement devices can be technically combined with the PIMEX system.

Two different tests were executed. In the first test, a CPC (Grimm type 5.403, serial number 54300907) was used. The CPC was coupled to an RS232-to-analogue converter (Grimm model 160, serial number 160-171008), which transports the signal as a voltage parameter (in millivolts) to the laptop and connected to the PIMEX set. Particles in a size range from 5 nm to 3 μm were counted with a flow of 0.3 l min^{-1}. The CPC was set up to generate a measurement value every second. It can be used for up to a maximum of 6 h without an external power supply.

A voltage divisor specially developed by the authors for this type of CPC was connected to the RS232-to-analogue converter of the PIMEX set. With this device, the measuring range could be set in three different modes, with a maximum of, respectively, 10^4, 10^5, and 10^6 p cm^{-3}. For the video images, a video camera (JVC, model GR-D 240E) was used (model GR-D 240E) was used and by means of a video capture device (Belkin video-bus) connected to the same laptop.

The CPC coupled to PIMEX was tested in practice for diesel emissions and a laser printer. Diesel emissions were measured on a parking lot. A car drives in reverse with the exhaust directed toward the CPC. A big spike was recorded up to $>$100 000 p cm^{-3}. After the motor was turned off, the concentration decreased quickly to the background concentration. In the chart, the indicated 1000 mV corresponds to 100 000 p cm^{-3}.

For the second test movie, an office table printer was used and emissions were recorded by the CPC. The concentration was $\sim$9000 p cm^{-3}, corresponding to $\sim$9 mV in the chart. In this example, no peaks can be seen but a steady state of increased concentration. A normal nanoparticle concentration in an office space lies between 3000 and 6000 p cm^{-3}.

In the second test, the Aerasense NanoMonitor (Philips Aerasense) was used together with the PIMEX-2008 software. The NanoMonitor detects airborne particles from 10 to 300 nm and was tested with a sample interval of 3 up to 9 s. The gain for the analogue output was set at 50 p cm^{-3} mV^{-1}. The analogue output of the NanoMonitor was linked to the PIMEX transmitter. In this configuration, it was possible to measure wirelessly and the signals are picked up by a receiver that is attached to the laptop. Measurements were taken during a relatively low-power welding operation. The PIMEX set recorded an operator welding with local exhaust

Table 1. Overview of available measuring instruments and some technical specifications

Type of instrument	Direct reading	Analogue output	Portable	Personal
 CPC	Yes (1 sec)	Yes	Yes	No
 Portacount	Yes (1 sec)	No	Yes	Yes
 Nanocheck	Yes/no (10 sec)	Yes	Yes	No
 NanoTracer	Yes (3 sec)	No	Yes	Yes
 NanoMonitor	Yes (3 sec)	Yes	Yes	Yes
 AeroTrak	Yes (1 sec)	Yes	Yes	No
 LQ1	Yes (2 sec)	yes	yes	no

ventilation used as a risk management measure (Fig. 3). By increasing the distance from extraction to the source after a few minutes, the recorded concentration of nanoparticles also increased, as can be seen in the graph.

To analyze the effectiveness of the PIMEX method in a measurement strategy where observations and near field as well as background concentration measurements are required, both CPC and NanoMonitor were tested with PIMEX-2008 software in a glass nanocoating process. The portable NanoMonitor was mounted close to the operator's breathing zone and the CPC was placed a few meters from the process in order to measure background concentration. The continuous concentration signals from both devices were transmitted to the computer using Bluetooth and radio modem connections. Using this technique, some near-field concentration peaks were observed, whereas background levels stayed low (Fig. 4).

DISCUSSION AND CONCLUSION

Both the CPC and the NanoMonitor are suitable for coupling with PIMEX and satisfy the technical requirements. Depending on the nature of the test or process, a decision can be taken on the most suitable instrument.

The CPC appeared not to be suitable for personal air sampling; yet, it is portable and can be located

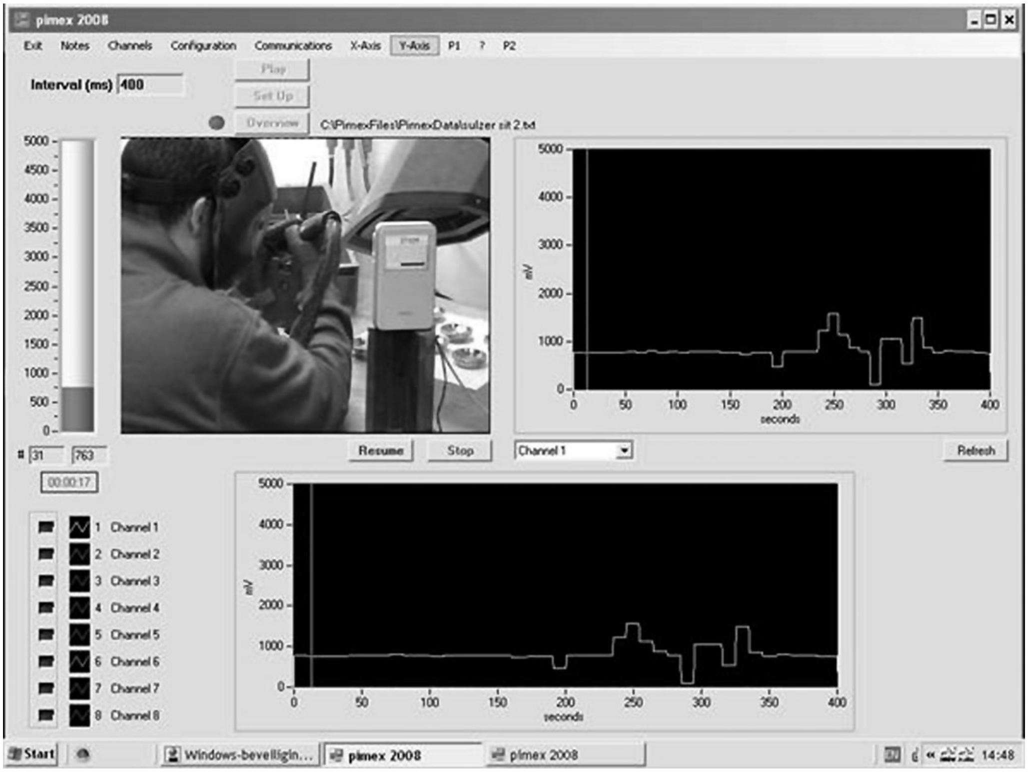

Fig. 3. PIMEX image using PIMEX-2008 software and a NanoMonitor for testing near-field measurements at a welding process recording the effect of distance of the local exhaust ventilation to the welding source.

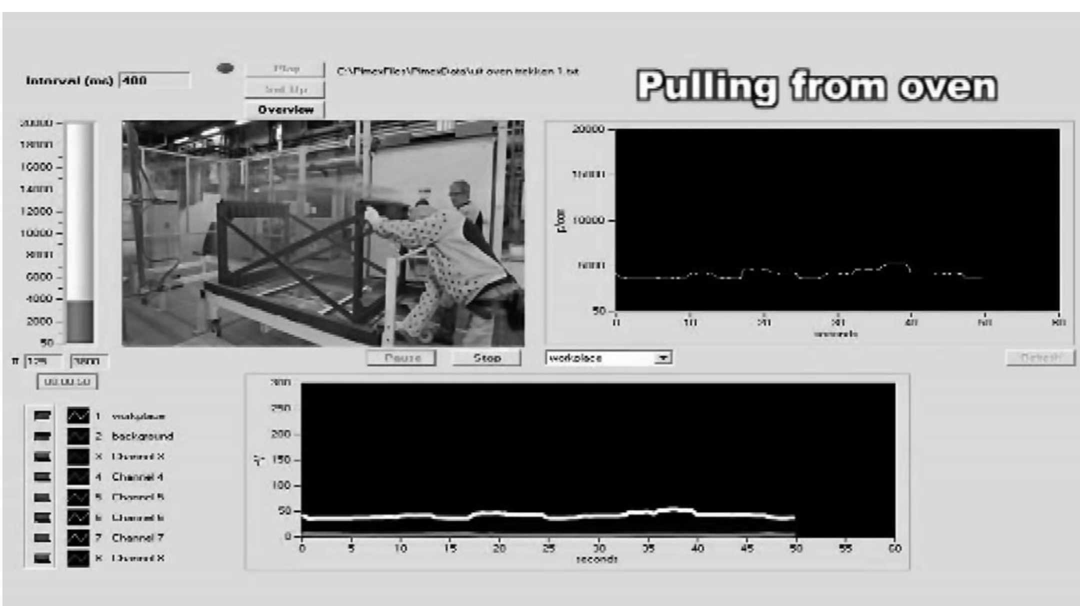

Fig. 4. PIMEX image from a nanocoating glass situation, measured with two devices. The white line in the graph on the right and below presents the exposure, and the gray line in the graph below is nearly zero and represents the background concentration of nanoparticles per cubic centimeter.

near the breathing zone in order to measure inhalation exposure to nanoparticles. The CPC is easy to use, with direct reading values. One drawback is that when large fluctuations in concentration are found, the data line quickly rises out of the range of the chart (this is only a limitation of the earlier PIMEX software). With the specially developed switch, the measuring range can be set in three stages with a variation of a factor of 10. Switching during a measurement must, however, be avoided. Using the PIMEX-2008 software overcomes this problem because data can be directly registered as particles per cubic centimeter instead of millivolts and the scale will set automatically to the registered concentration in particles per cubic centimeter.

The NanoMonitor is easy to use and to connect to PIMEX. It can also be used for personal air sampling. A tube for transportation of the sample from the breathing zone is not included as standard (the NanoMonitor is referred to as a wall monitor device for connection to air management systems) but can be supplied as an accessory. In the graph next to the video image on the screen, the concentration is given in p/cm^3 instead of millivolts, unlike the earlier version of the PIMEX software which only showed millivolts. One disadvantage is the automatically programmed zero check which occurs every 5 min and has a duration of 12 s and the last measured value is displayed for those 12 s. This is not desirable in a short PIMEX video lasting about 1 min, especially since in the chart these zero checks are not recognizable. In practical terms, this can be solved by starting with the recording, right after a zero check. Similarly, the interval between two checks can be changed (by the supplier) to, e.g. 15 min. This frequent calibration may be necessary when the instrument is used to monitor exact values. The basic idea with VEM is not so much to present exact values but rather to visualize the variation. So the calibration may then not be as important compared to other uses of the instrument.

For both CPC and NanoMonitor, measuring parameters are given in particles per volume unit; only the NanoMonitor gives the (arithmetic mean) nanoparticle size, making the measurement data more precise.

The different size ranges of both devices are a possible explanation of the difference in concentration the authors experienced while placing both instruments at the same location. Concentration levels of the CPC were about 30% higher than values of the NanoMonitor.

Other measuring instruments like AeroTrak and LQ1 also seem suitable for combination with PIMEX. Both devices measure surface area concentration thus might be better suited to specific health risk studies. These devices have not been tested in this study.

Both PIMEX versions can be used for measurements of nanoparticle exposure. The advantage of the newer version is the ability to connect two or more devices simultaneously to register and display exposure and the ability to show measuring units as p/cm^3 directly in the graph instead of millivolts.

PIMEX or other VEM techniques are useful tools for exposure assessment to nanoparticles. We found that the use of VEM was helpful in locating work activities associated with emission of (manufactured) nanoparticles. The results from VEM help to understand exposure in detail. Video images support the observation of the work process as a part of the strategy to assess exposure. It is an effective way of identifying parts of the process that could lead to worker's exposure to hazardous nanoparticles. Having the ability to measure with two instruments simultaneously (e.g. at two different locations), it is also possible to instantaneously distinguish the background concentration from the manufactured nanoparticles released from the process. In order to make a good interpretation of the contribution of ambient sources to the total concentration, it is necessary to use two or more of the same type of measuring devices. As total concentrations in p/cm^3 can vary between different types of instruments, even if they are based on nearly the same measurement principles, it is recommended to use the same devices simultaneously in order to prevent misinterpretation of the measured concentrations.

VEM can be used as part of a strategy to assess exposure to nanoparticles and undertake workplace air measurements in line with the good-use-decision-tree approach. The overall strength of VEM is determined by the strength of the individual components. The device response to particle concentration results from the detection of any aerosol and not necessarily from only the manufactured nanoaerosols. Hence, it is clear that additional characterization, e.g. by off-line analysis of samples is still required for an appropriate interpretation of the results.

PIMEX showed to be effective in identifying peak exposure for quality and control measures (European Agency for Safety and Health at work, 2003). Use of real-time measurement and graphics promotes new ideas for improvement to the working environment. These benefits also apply to working situations with nanoparticle exposure because with VEM methods measurement and control of a process is possible.

This study was undertaken within the context that a standardized strategy to assess exposure in the workplace is currently not yet available but nevertheless precautionary measures are becoming more important in the occupational environment. Also there is no standard agreement on which characteristics need to be measured. In the near future, knowledge regarding the risks will expand, new guidelines on measurement strategies will become available, and technical capability of measurement devices will grow. The conclusions of this study may be influenced by these developments and new insights and advances in equipment may lead to revised conclusions and even greater possibilities.

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