Real-Time Measurement of Personal Exposure to Airborne Nano-Objects with the DiSCmini

Part 2 – Application Examples of the DiSCmini

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ABSTRACT The use of the DiSCmini has developed considerably in the context of evaluating inhalation exposure to nanoparticles. This article presents the results obtained during measurement campaigns at workplaces. A few examples describe the applicability of the DiSCmini to measure nano-objects in different metrics complementary to standard exposure measurement methods.
This article is the follow up of the instrument's working principle description and laboratory comparison [1], that showed its ability to determine personal exposure to ultrafine particles and nano-objects in the size range below approximately 700 nm. Besides the number concentration, also the surface area concentration as well as a mean diameter of the aerosol is determined. The DiSCmini is one of the few instruments allowing person mounted use to measure directly the personal exposure to ultrafine particles. For a more comprehensive exposure determination, other instruments can be useful like direct reading instruments for the size range above 700nm, in addition to conventional aerosol samplers for mass concentrations. Although occupational exposure limit values for a number concentration are not in use for ultrafine particles or nano-objects, number based reference values can be chosen for an assessment of the exposure [2]. Such easy to use instruments like the DiSCmini can also be used in a tiered approach for exposure determination of nano-objects as described in a European Standard [3]. The first two phases of the latter approach is a suitable application to get an overview of the concentrations. Another application for such direct reading instruments will be the assessment of protective measures at particle emitting processes, e.g. the application of local exhaust ventilation [4]. Further experience in using the DiSCmini in the laboratory and the field was described in [5, 6, 7], while a review on exposure measurement methods for nano-objects is given in [8]. The following part describes examples of use of the DiSCmini and should help the reader to plan such applications and show which data can be expected.

Echtzeitmessung der persönlichen Exposition gegenüber luftgetragenen Nano-Objekten mit dem DiSCmini

Teil 2 – Anwendungsbeispiele

ZUSAMMENFASSUNG Der Einsatz des DiSCmini hat sich hinsichtlich der Bewertung der inhalativen Exposition gegenüber Nanopartikeln deutlich weiterentwickelt. In diesem Artikel werden die Ergebnisse von Messkampagnen an Arbeitsplätzen vorgestellt. Einige Beispiele beschreiben die Anwendbarkeit des DISCmini zur Messung von Nanoobjekten in verschiedenen Metriken, die die Standardmethoden zur Expositionsmessung ergänzen.
Dieser Artikel ist die Fortsetzung der Beschreibung zum Funktionsprinzip des Geräts und des Laborvergleichs [1], der gezeigt hat, dass es in der Lage ist, die persönliche Exposition gegenüber ultrafeinen Partikeln und Nanoobjekten im Größenbereich unter etwa 700 nm zu bestimmen. Neben der Anzahlkonzentration werden auch die Oberflächenkonzentration und ein mittlerer Durchmesser des Aerosols bestimmt. Das DiSCmini ist eines der wenigen Geräte, mit denen die persönliche Exposition gegenüber ultrafeinen Partikeln direkt gemessen werden kann. Für eine umfassendere Expositionsbestimmung können andere Instrumente nützlich sein, z. B. direkt ablesbare Instrumente für den Größenbereich über 700 nm, zusätzlich zu herkömmlichen Aerosolsammlern für Massenkonzentrationen. Obwohl für ultrafeine Partikel oder Nanoobjekte keine Arbeitsplatzgrenzwerte für eine Anzahlkonzentration verwendet werden, können anzahlbasierte Referenzwerte für eine Bewertung der Exposition gewählt werden [2]. Einfach zu bedienende Geräte wie das DiSCmini können auch in einem stufenbezogenen Ansatz zur Expositionsbestimmung von Nanoobjekten verwendet werden, wie in einer europäischen Norm beschrieben [3]. Die ersten beiden Phasen des letztgenannten Ansatzes sind eine geeignete Anwendung, um einen Überblick über die Konzentrationen zu erhalten. Eine weitere Anwendung für solche direktanzeigenden Instrumente wird die Bewertung von Schutzmaßnahmen an partikelemittierenden Prozessen sein, z. B. die Anwendung lokaler Absauganlagen [4]. Weitere Erfahrungen mit dem Einsatz des DiSCmini im Labor und im Feld wurden in [5 bis 7] beschrieben, während ein Überblick über Expositionsmessmethoden für Nanoobjekte in [8] gegeben wird. Der folgende Teil beschreibt Beispiele für den Einsatz des DiSCmini und soll Leserinnen und Lesern helfen, solche Anwendungen zu planen und aufzeigen, welche Daten zu erwarten sind.

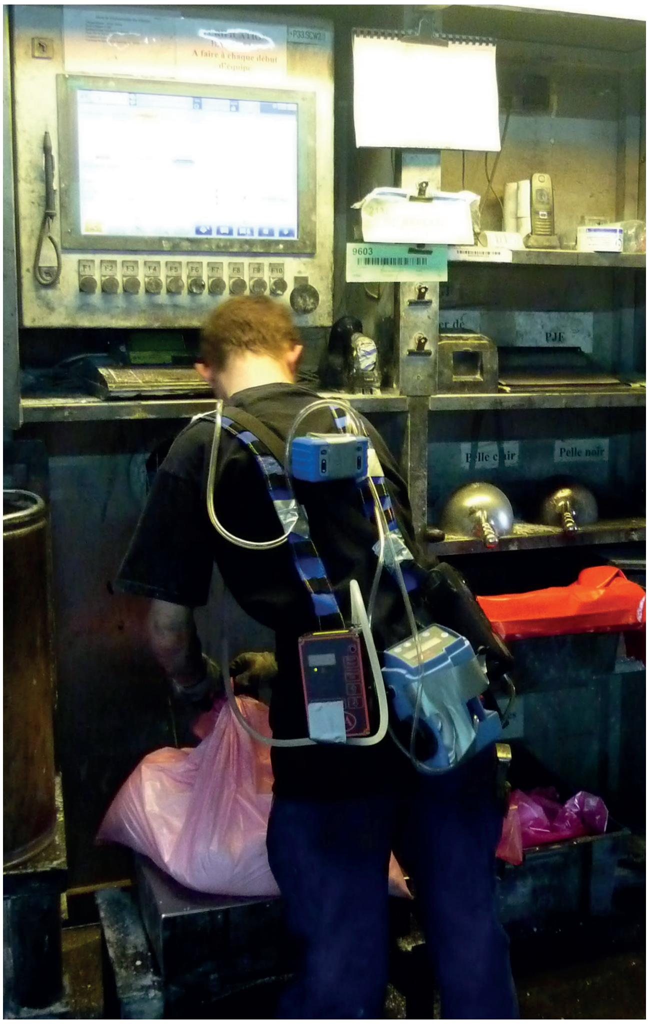

Figure 1 Weighing operation with an operator closing the weighed bag of powders at the workstation and carrying the real-time measuring instruments, including the DiSCmini. *Source: ©INRS*

1 Example 1: Assessment of weighing operations

In this example of the DiSCmini use [9], only the number concentrations of aerosols are represented, so as to facilitate the reading. A picture representative of one of the work tasks is provided in **Figure 1**. In the same way, the time profiles resulting from the real-time measurement of the modal diameter of particles can also be represented to complete the data interpretation. The particle number concentration provided by the DiSCmini mounted on the operator during powder weighing operations is presented in **Figure 2**. These measurements were carried out in the context of the ExproPNano research project, funded by Anses, which the INRS contributed to. On this time profile, the aerosol number concentration measured simultaneously using another DiSCmini against a point of reference is also displayed. This position was chosen as not to be influenced by the activities carried out by the operator. This series of data is called "background aerosol". The preliminary investigations conducted in the laboratory and described in part 1 enabled a good correlation to be established (relative deviations less than 20 %) between the two models implemented here.

In the interest of readability, the time profile in Figure 2 is shown only over a short period of time, around 15 minutes. Indeed, the operation was accompanied by a detailed analysis of the work activity performed by VEM (Video Exposure Monitoring) using the CAPTIV® tool (Centrale d'acquisition de la pollution au travail informé par vidéo) developed by the INRS [10], as described in a recent proposal stemming from the feedback accumulated in the context of the ExproPNano project [11]. Thus, throughout the workstation, the activities conducted by the operator were observed and classified into different categories according to the thesaurus mentioned in **Table**, corresponding to the different colours. Consequently, this description offers the possibility of determining, at a given workstation, the actions that are correlated to the highest levels of exposure, and to implement adapted protective measures. It is worth noting that the minimum time frame used for the coding of activities should be consistent

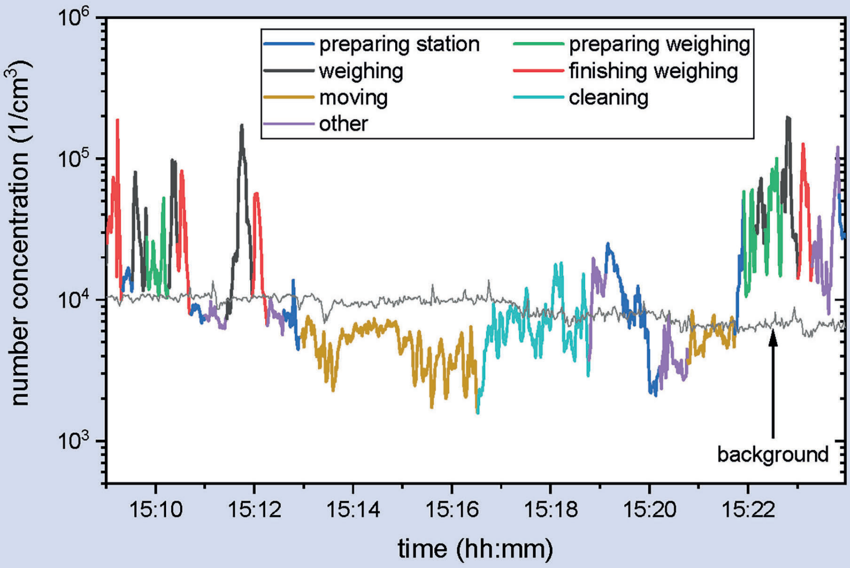

Figure 2 Example of time profile linked to an analysis of the activity. *Source: ©INRS*

Table Thesaurus and description of the operator's actions.

TITLE	DESCRIPTION
Preparing station	The operator interacts with the computer, sets up a new bag, changes the bag holder, etc.
Preparing weighing	The operator recovers and opens new bags of raw materials to be weighed. Powder containers can be transported.
Weighing	The operator weighs using 15 kg to 25 kg bags or big bags.
Finishing weighing	The operator closes the weighed bag by tying a knot.
Moving	The operator moves around on foot or using an electric trolley.
Cleaning	The operator cleans the workstation with a broom.
Other	Any actions that do not fit into the categories described above.

with the device's response time. For the DiSCmini, whose response time is around 7 seconds [1], a time interval of 10 seconds was chosen.

Figure 2 reveals that the activities under "Weighing" (in black) and "Finishing weighing" (in red) correspond to the highest concentration levels. Over the total duration of monitoring the workstation (1.5 h), these activities represent nearly 50% of the time, and the concentrations detected are around seven times higher than those detected at background aerosol level (approximately 10 000 particles per cm³, averaged over the duration of the operation). Similarly, the activity named "preparing weighing" (in green), corresponding to 11% of the time, leads to number concentration measurements that are around two times higher than those for the background aerosol. On the contrary, during the operator's movements around the workstation (in yellow), the concentration measured is equivalent to that obtained for the background aerosol or even lower when moving outside the work area or at fresh air spots. With a view to reduce occupational exposure at the investigated workstation, recommendations could be made, such as the implementation of an extraction torch for the weighing of powders. The use of personal protective equipment during operations with the highest amount of exposure could constitute the ultimate choice.

2 Example 2: Grinding of nanocomposite material

A workplace for sanding nanocomposite materials was investigated for its exposure situation in the German research project nanoGRAVUR. Exposure tests were carried out with a belt grinder (7.25 m/s) in a ventilated test chamber (4 m², 10 m³, 30 m³/h) for 20 min and three repeats each (**Figure 3**a). Air-borne particle emissions were measured with a set of different instruments (Figure 3b), either at fixed positions next to the process and the worker as well as at the person. The DiSCmini (Testo, Titisee-Neustadt, Germany) was mounted at the person together with an aerosol sampler for conventional respirable dust (FSP 2 cyclone, 2 l/min, GSA Schadstoffanalytik, Ratingen, Germany).

Epoxy resin with 2% by weight SiO_2 nanomaterial (Aerosil 200, Evonik) was used as nanocomposite material in 4 mm thick sheets for the sanding/grinding processes that are marked in the timeline of **Figure 4** (three times for 20 min each). The mass concentrations of respirable dust were in average of the three sanding processes 1.1mg/m³ (FSP 10 cyclone, 10 l/min, GSA Schadstoffanalytik, stationary sampling at 1m distance) and 3.1mg/m³ (personal sampling with FSP 2).

The number concentrations in one meter distance from the process for particle sizes below about 1 µm were in average 12 000/cm³ (CPC 5403, Grimm Aerosol Technik, Ainring, Germany, 10 min each selected for averaging). Data from SMPS (3936, TSI, Shoreview, USA) and another CPC (3007, TSI, directly next to process) were very similar. The average number concentration measured by the APS (3321, TSI) was 229/cm³, but limited to the size range from 0.5 to 20 µm. In contrast, the average number concentration determined by the DiSCmini was 137 000/cm³, which is the tenfold of the CPC values. This overestimation was similarly detected at the sanding processes of other nanocomposite materials in the same setup. A few reasons seem to contribute to this effect. The distance of the DiSCmini was

Figure 3a Workplace for sanding nanocomposite materials with a set of particle measuring instruments. *Source: IFA*

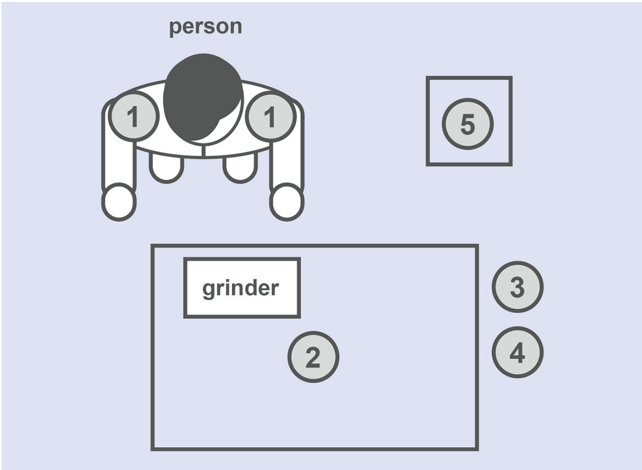

Figure 3b Setup of measurement instruments (1: DiSCmini and FSP 2, 2: CPC 3007, 3: sampling point for CPC 5403 and SMPS, 4: FSP 10, 5: APS and other instruments). *Source: IFA*

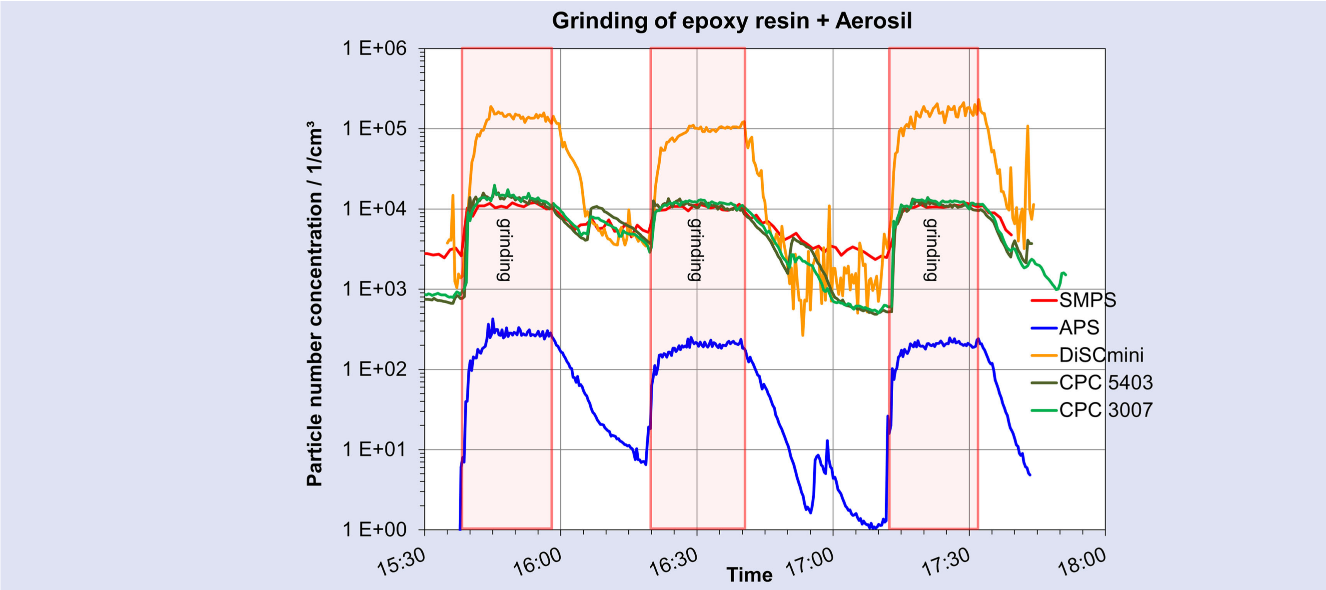

Figure 4 Particle number concentrations during sanding of nanocomposite material (epoxy resin with nano sized SiO_2). *Source: IFA*

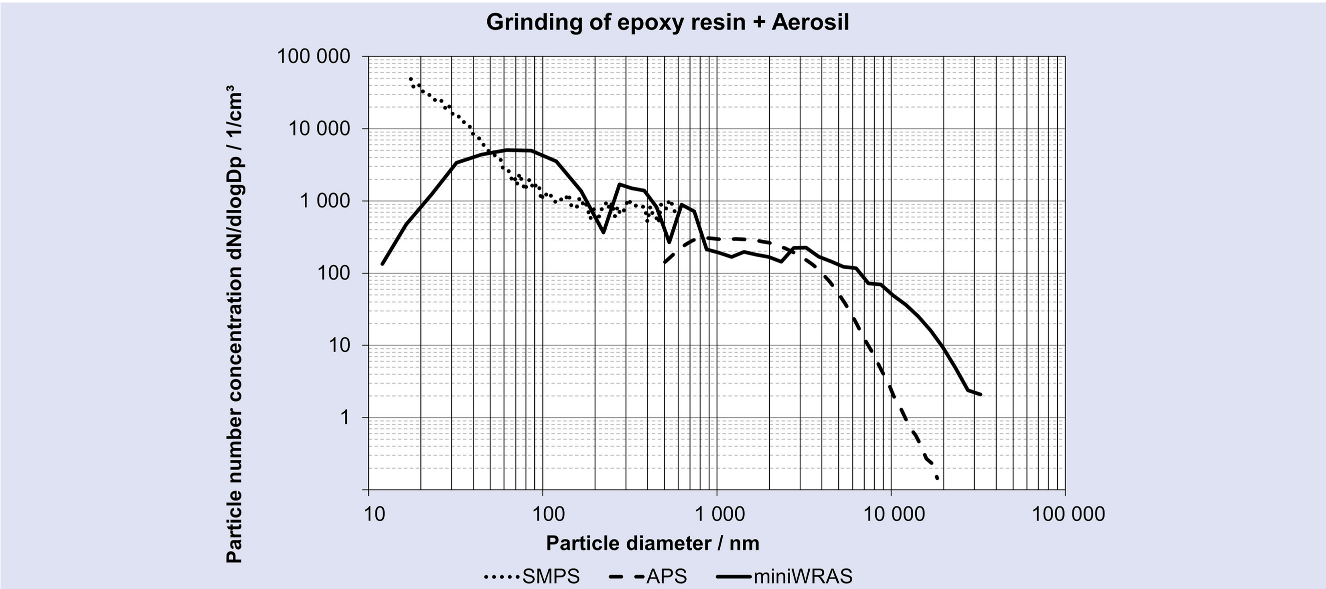

Figure 5 Particle size distribution during sanding of nanocomposite material (epoxy resin with nano sized SiO_2); miniWRAS type 1371 (Grimm Aerosol Technik, Ainring, Germany). *Source: IFA*

somewhat different and nearer to the process than the sampling line of the CPC 5403 and SMPS, except for the CPC 3007 (Figure 3b). As the dust concentration was quite high (appr. 3 mg/m³ at the person), the inlet impactor could be overloaded and many particles in the higher particle size range of the DiSCmini (up to 700 nm and larger) were transferred to the diffusion charger and could contribute to false positive counts. If large particles reach the sensing zone of the DiSCmini, they are assumed to be multiply charged and thus counted/considered as smaller sized particles.

The particle size distribution is given in **Figure 5**. A constant increase of particles towards small sizes was detected, still remaining plenty of particles in the higher size range of the DiSCmini of several hundred nanometers (200 to 1000/cm³).

The DiSCmini is also capable of determining a modal diameter of the aerosols sampled, limited to the range from 10 to 300 nm. In this example the modal size diameter was calculated to approximately 14 nm during sanding processes which fits to the size distribution measured by the SMPS (**Figure 6**). When ventilating the workplace with clean air between sanding operations, the number concentration decreased while the particle size provided by the DiSCmini increased (similar to the mean diameter in SMPS data as the smaller size range of a few ten nanometers is reduced). As the diameter value is evaluated from a ratio of measured electrical currents in the sensing zone inside the DiSCmini, stable values of the currents are important. The situation gets more unstable at concentrations near 1000/cm³ as this corresponds to the instrument's lower concentration limit. This can be seen in the example in Figure 6 around sampling time 17:00. Here the diameter values are no longer useful.

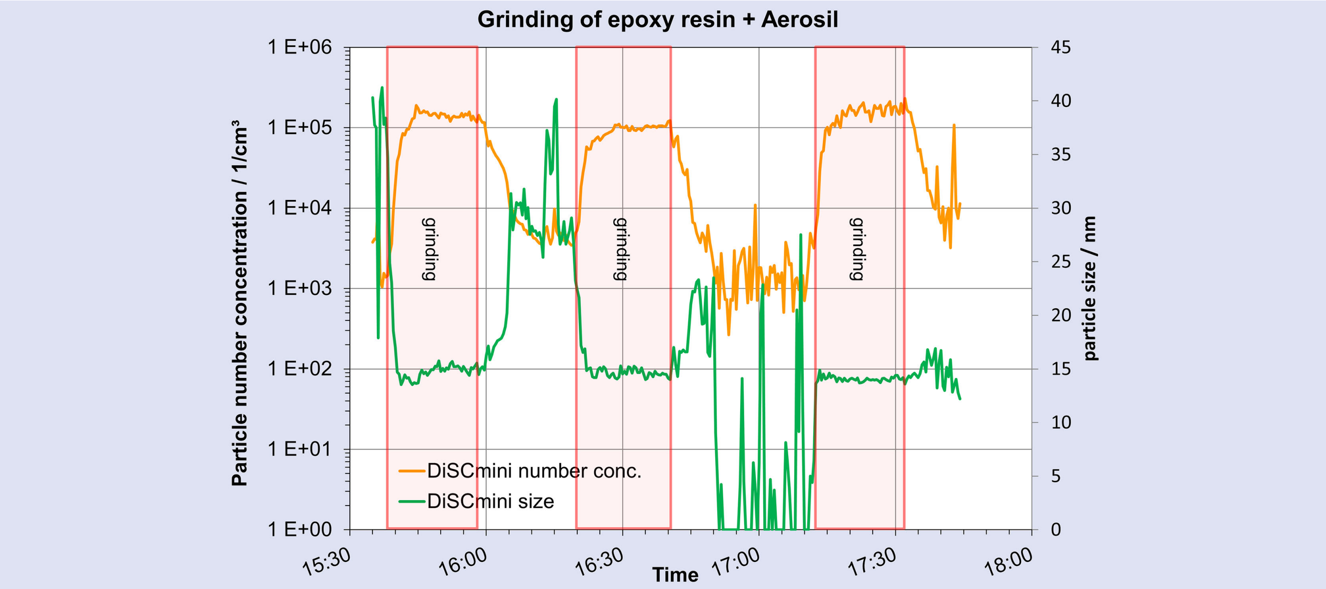

Figure 6 Particle number concentration and particle diameter determined by DiSCmini during sanding of nanocomposite material. *Source: IFA*

3 Example 3: Firework on theatre stage

Several theatre shows use fireworks and pyrotechnical effects on stage (**Figure 7**). During such short time effects, emissions arise and can reach a part of the actors crew. During testing these effects in rehearsal stage, the particle concentrations were measured above the stage on the catwalk where actors sometimes have to go into or out of a scene. The measurement results of a DiSCmini are given in **Figure 8**. The number concentration ranged up to 250000/cm³ during this one hour of stage activity at the upper part of the stage that can not be seen by the audience. Two times (11:12 and 11:43), short pyrotechnic effects of about half a minute were ignited and clouds of fume driven towards the ceiling. It takes at least 10 minutes for the concentrations to decrease towards the preceding range. As already stated, occupational exposure limit values do not exist for particle number concentration. Nonetheless, these data can be used to assess the quality of the ventilation and propose additional protective measures. The particle size of about 175 nm was nearly constant during the whole period after ignition of the effects (green curve). Additionally, the surface area concentration[1)] is calculated by the software and displayed in Figure 8 (blue curve, note that the right axis has exponential scale). The mass concentration was calculated manually from each measurement point of the DiSCmini by assuming spherical particles with a density of 0.5 g/cm³ for the fumes (grey curve). In average over the time displayed the mass concentration can be assumed to be 0.16 mg/m³.

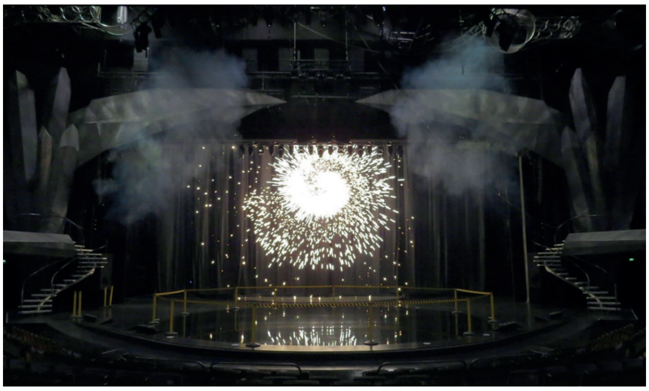

Figure 7 Burning of the central pyrotechnic effects on stage. *Source:* Unfallkasse Berlin

Conclusions

Direct reading instruments in workplace air can be a helpful tool to determine the particle concentrations. Especially small rugged instruments like the DiSCmini can be mounted at a person to achieve exposure information in the breathing zone. If personal aerosol samplers are applied, the data on average mass concentration can be used to calibrate the time series from the aerosol monitor.

The DiSCmini allows the determination of number concentration, surface area concentration and an average particle diameter with a time resolution of one second. Its size range between 10 and approximately 700 nm allows to determine number concentrations between 10^3 and 10^6 particles per cm³, which is a sufficiently broad range for a variety of workplaces.

A monitoring strategy for nano-objects is described in the European Standard EN 17058 [3]. In such a tiered approach, particle monitors like the DiSCmini can be an easy to use instrument to determine the concentrations during the first steps to get an overview of concentrations and particle sources over time and different locations. In order to assess the workplace emissions only, the background can be measured separately with a second aerosol monitor. The limits of application must be considered and a regular calibration is advisable, either recommended by the manufacturer or according to the frequency of use by the user. High dust concentrations can lead to artificially increased number concentrations so that different types of instruments can be a valuable control.

[1)] The DiSCmini determines the lung deposited surface area (LDSA) concentration of the particles in its size range

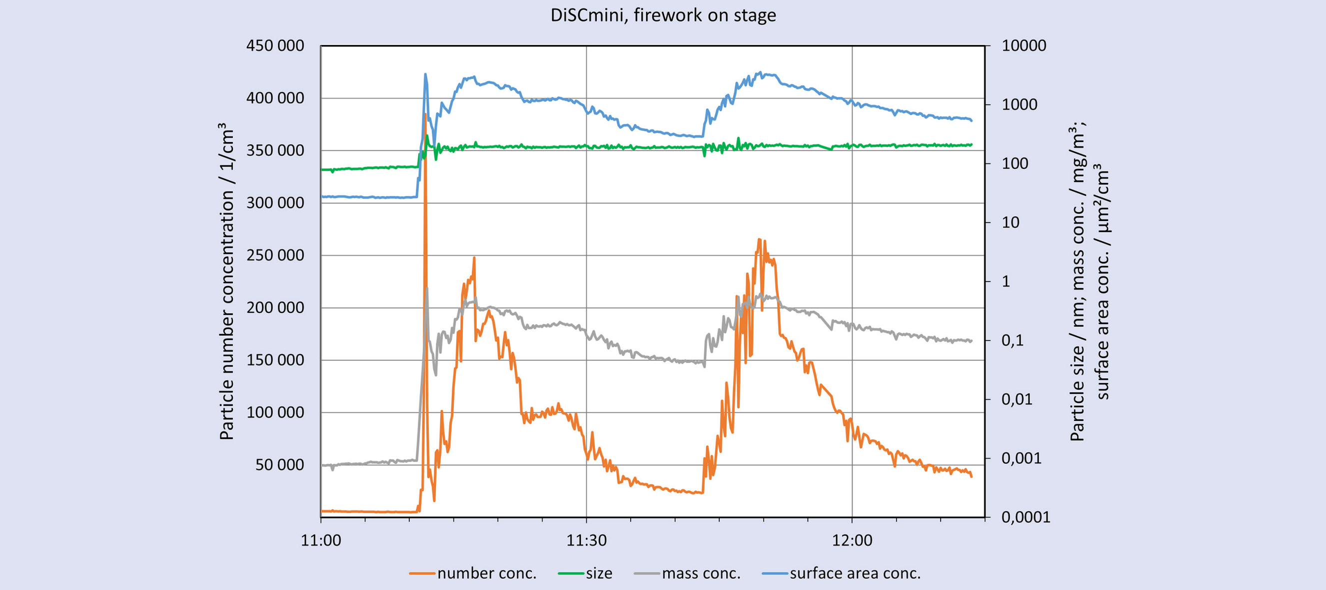

Figure 8 Fume concentration at the catwalk during firework on stage expressed in different metrics. *Source: IFA*

Finally, the use of direct-reading measurement devices is of particular interest if it is accompanied by a relevant observation of the process and worker's activities. Video exposure monitoring tools combining video captures with measurement data can be a valuable help to discover processes of high dust emissions. A review of such findings allows the worker and the company to avoid such situations and to apply suitable protective measures. ■

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