Measuring respirable aerosol with real-time optical monitors

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1. Introduction

This chapter provides basic guidelines for using direct-reading monitors to measure respirable aerosol mass concentrations in different occupational environments in real time[1]. There is not a definitive consensus on what constitutes a direct-reading methodology. Technological changes and the increased use of direct-reading instruments and methods constantly shift what the health and safety community defines as such. A real-time monitor is a specific type of direct-reading instrument that detects, reacts, and measures the contaminant of interest in a short period of time in which the appropriate response time is defined by the application. A real-time monitor can generate a time series of measurement data. Hereafter in this chapter, the terms *real-time respirable aerosol monitors* or simply *monitors* will be used. Real-time respirable aerosol monitors generate a signal that is proportional to the concentration of respirable aerosol in the sampled air, above a minimum detectable level. The signal generated by the monitor can be displayed and recorded as a measurement datapoint in an internal datalogging system or in a cloud space.

The great majority of real-time respirable aerosol monitors used by industrial hygienists and health and safety professionals work through the interaction between light and aerosol particles. These can be called light-scattering dust monitors, photometers, nephelometers, optical dust monitors, or optical particle counters. Each name refers to a sensor that uses a slightly different measurement principle. Basic descriptions of the sensor types will be provided in a later section of this chapter. Although the term *respirable dust* is common, *respirable aerosol* is more appropriate and in-line with other NMAM chapters, so it will be used in this chapter. The monitors are generally battery-operated, hand-held or at least portable, and used for area or even personal monitoring. These monitors can provide the mass concentration of respirable aerosol in a workplace with benefits in terms of 1) immediate results compared with the laboratory gravimetric method and 2) time-resolved data throughout the monitoring period. Additional applications of the real-time respirable aerosol monitors are also described in this chapter. This chapter focuses exclusively on real-time monitors that use optical measurements to measure respirable aerosol. A few other monitors use different analytical approaches, such as tapered element oscillating microbalances, but those are not considered in this chapter.

[1] This chapter is a revision of Chapter G (Aerosol Photometers for Respirable Dust Measurements), written by the late Dr. Paul Baron and included in the 4th edition of the NIOSH Manual of Analytical Methods: NIOSH [1994]. NIOSH Manual of analytical methods [NMAM]. 4th ed. Schlecht PC, O'Connor PF, eds. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 94-113, https://www.cdc.gov/niosh/nmam/default.html. Although this chapter follows the structure of the original chapter, information and terminology have been updated to reflect the most current practice. Specific sections on the field calibration of the monitors and the application of the data have been added as a result of the last twenty years of published studies.

Respirable aerosol is defined as airborne particles likely to reach the gas exchange region of the lungs, where removal mechanisms are less efficient compared to upper airways. Respirable aerosol is defined by the international convention criteria [Bartley et al. 1994; ISO 1995; Vincent 1998], which is recognized in the United States by the National Institute for Occupational Safety and Health (NIOSH) and other entities. The convention defines a respirable aerosol based on the aerodynamic diameter of each particle and the percent of the various particle diameters that make up the composition of that aerosol. The percent value for respirable aerosols is very low (1%) for particles with a diameter of 10 micrometers (μm), 50% for particles with a diameter of 4 μm, and almost 100% for particles smaller than 1 μm. More information on respirable aerosol and conventions can be found in NMAM Chapter AE (Factors affecting aerosol sampling) [NIOSH 2014b].

The information and guidelines provided in this chapter can be applied even if different conventions for respirable aerosol are used. Although real-time aerosol monitors might be utilized to monitor other fractions of particles or total dust, the broader need for aerosol monitors is not the focus of this chapter. In addition, this chapter does not discuss real-time portable condensation particle counters that provide particle number concentration in a unit of air volume. These are generally used to measure ultrafine particles that are particles with a characteristic dimension smaller than 100 nanometers, such as diesel particulate matter, welding fumes, engineering nanoparticles, or aerosols from hot processes. Aerosols composed of ultrafine particles and engineered nanoparticles generally include larger respirable agglomerate. For this reason, some studies have explored the use of real-time respirable aerosol monitors for these aerosols with good success. [Dahm et al. 2013; Evans et al. 2010]. Studies have reported on the use of ultrafine particle counters for respirable aerosols in occupational environments. However, this practice is not recommended because these monitors are limited in the size range of the particles they detect and their upper limits of concentration are inadequate [Jenkins et al. 2004; Wallace et al. 2011].

Recently, several Consumer Aerosol Monitors (CAM) were made commercially available for activities such as air quality monitoring, citizen science, and community engagement. CAMs, sometimes referred to as low-cost aerosol monitors, are designed and developed for public ambient aerosol and indoor air monitoring, but they are slowly finding application in the workplace [Ruiter et al. 2020]. CAMs generally adopt similar measurement principles as those used in the real-time respirable aerosol monitors designed for industrial hygiene professionals covered in this chapter. Since CAM adoption by industrial hygienists is still limited at the time this chapter was prepared, they are not included. However, some information about CAMs can be found in a fact sheet recently published by the American Industrial Hygiene Association (AIHA)[AIHA 2021].

This chapter can be helpful for different type of users of direct-reading methodologies as defined by a framework recently published by the AIHA real-time detection systems committee [AIHA 2020]. Other

resources and guidelines can be found in a document published by the European Committee for Standardization [CEN 2010].

2. Principle of operation

Several real-time respirable aerosol monitors intended for use in occupational environments are commercially available. Although each monitor has unique characteristics, common components are generally present: a particle size preselector, a sensing element, a filter media, and a sampling pump. Understanding the role of each component is important for knowledgeable selection and implementation the l device with its inherent capabilities and limitations. Each monitor has the capability to measure and record data at different frequencies, down to one datapoint per second for some monitors. The frequency should be selected based on the monitoring application and data storage capacity, as an ideal frequency does not exist.

Some monitors can also be used in potentially explosive atmospheres, such as in oil, gas, and mining workplaces. In order to be used in these environments, the monitors must be certified as intrinsically safe from an electrical perspective. It is important to note that intrinsically safe regulations can vary by country.

a. Preselector or size selective inlet

In order to perform respirable aerosol monitoring, the monitor should be capable of measuring respirable aerosol particles. To facilitate this process, a size selector or preselector (cyclone or impactor) can be employed to remove large nonrespirable particles from the sampling airstream, thereby allowing only respirable particles to reach the sensing element of the monitor. Detailed information on aerosol sampling and the use of preselectors can be found in Chapter AE (Factors affecting aerosol sampling) [NIOSH 2014b].

Some real-time respirable aerosol monitors have an integrated internal size selector or an external size selector; the latter is most often used in filter-based samplers for respirable aerosol. The size selector should be properly maintained and periodically cleaned to avoid excessive buildup of large particles that could enter the sensing element and potentially alter the preselector's performance. Most real-time respirable dust monitors with a photometer sensor will have a size preselector. However, optical particle counters might not need a size preselector to ensure the measurement of respirable aerosol particles. This is because they are capable of counting each particle and assessing the particle size. From these two measurements, these monitors can create a particle size distribution. After applying a respirable convention model, they can then provide a measurement of respirable aerosol concentration.

In some monitors, a line of tubing is used to transfer the respirable aerosol from the size selector to the sensing element. Aerosol flowing through the tubing can be attracted to the tubing walls via a static effect. This is created by an electrical potential on the walls of the tubing when certain plastic materials are used,

such as polypropylene or flexible polymer tubing. Tubing comprised of a conductive material, such as carbon impregnated conductive silicone, metallic, or conductive flexible tubing, should be used to minimize the losses of aerosol during the transfer. Keeping tubing lengths to a minimum and avoiding sharp bends are key aspects to consider.

b. Sensing element

The sensing elements used by the real-time monitors covered in this chapter operate by illuminating aerosol particles passing through a defined volume and detecting and quantifying a signal resulting from the interaction of light and the aerosol. This interaction can be the total light scattered by all the particles in that volume, and in this category, photometers, nephelometers, or light scattering monitors are included. The light source can be of various types (monochromatic or broad wavelength). The scattering light is generally measured by the detector at a certain angle or angles. The amount of light scattered by the aerosol, and measured by the detector, is used to estimate, in real time, the relative mass concentration using algorithms specific for each monitor. The interaction of light and an aerosol particle is a complex function of several variables, including the particle size, shape, refractive index, and wavelength of light used. In addition, the density of the particle is a critical factor considered in the algorithm. The monitor response can be modeled to provide mass concentration of the aerosol for spherical particles of known refractive index.

Another optical technique employed by some monitors, such as optical particle counters, is single particle counting, which is the interaction of light and one particle at a time. This is still a light scattering or light-intensity approach. In this case, the challenge for the sensor is to count all the particles and to estimate the size of each particle. The combination of these two measurements, and an estimate of mass density, can provide aerosol mass concentration measurement. The measurement is still affected by particle shape, refractive index, and density. More information on the measurement techniques and their theories can be found in the literature [Hinds 1982].

For both measurement techniques, since particle mass is not directly measured, these monitors require calibration for their reliable use as mass concentration monitors. Monitors are factory calibrated with reference materials, such as Arizona Road Dust or oil microparticles, as well as other calibration aerosols as reported by manufacturers in their literature. The use of different materials should not be a surprise since the factory calibration with a generic standard material is conducted only to ensure that the monitor performs as expected. However, the factory calibration does not ensure an accurate measurement in the field with any other type of aerosol.

Many manufacturers refer to a factory calibration factor of 1.0 for a monitor that has just been calibrated. A custom calibration factor, described below in a section on field-calibration factors, can be different from 1.0 based on the specific environment and aerosol. The response of the sensing element can be different for different aerosol materials for monitors using both measurement techniques [Benton-Vitz and

Volckens 2008; Halterman et al. 2017; Patts et al. 2019; Soneja et al. 2014; Zuidema et al. 2019]. Results from a recent field study showed that concentrations measured by factory calibrated monitors can vary by up to a factor of 10 from filter-based respirable aerosol samplers and gravimetric analysis [Cauda et al. 2021].

To increase confidence in the accuracy of the data generated by a real-time respirable aerosol monitor in a specific environment, the data from each session can be corrected with the analysis of a gravimetric sample collected at the same time, or the monitor can be periodically calibrated in the field with the aerosol target of the monitoring activity. Benefits and limitations exist for each approach, which are presented in more detail in the section "Correction and field-calibration factors."

Finally, environmental conditions, such as temperature and relative humidity (RH), might affect the measurement of the sensing elements. Most real-time respirable aerosol monitors include temperature and RH sensors, and the measurement is adjusted in real-time.

c. Filter media

Sometimes a component of a real-time respirable aerosol monitor is a filter to collect the respirable aerosol after the sensing element. The most common use of the sample collected by the filter is for gravimetric analysis to correct the monitor reading or to field calibrate the monitor for a specific aerosol. This process is described in more detail in the section "Correction and field-calibration factors." The sample collected by the filter can also be analyzed to provide additional information about the aerosol collected, including analyses for crystalline silica and elemental metals. The selection of the right filter media depends on the type of analysis to be performed.

d. Sampling pump

Most real-time respirable aerosol monitors function in active mode, meaning that they pull air and aerosol into the sensing volume using a fan or a pump at a constant known volumetric flow rate. The pump's primary function is to provide constant volumetric flow through the monitor to the sensing element. The flow rate at which the monitor operates must be carefully selected and assessed before each use, because it also ensures the proper functioning of the size selector, if present, to segregate only the respirable fraction of the aerosol.

3. Correction and field-calibration factors

As explained above, the factory calibration with a generic standard material does not ensure that the calibrated monitor will provide accurate results for other types of aerosol in the workplace. This is because, as mentioned previously, the performance of a real-time respirable aerosol monitor can be affected by type of aerosol(s) monitored and environmental conditions.

The measurement accuracy from the monitor, in terms of single session time-weighted average respirable aerosol mass concentration, can be improved by the using one of two processes: 1) the calculation of correction factor for each session or 2) the development and adoption of a pre-established field calibration. Although these two processes are similar in the way they are executed, they are completely different in principles. Every time a user performs a monitoring activity with the real-time monitor, the data can be adjusted using a correction factor.

The correction factor basically corrects the data generated by the monitor. A correction factor for each session and each monitor can be calculated by requesting an analytical laboratory to conduct gravimetric analysis of the internal filter of the monitor (if present) or of a paired side-by-side sample collected with a filter-based sampler.

Alternatively, establishing a field-calibration factor for a monitor can be explored. The field calibration is a process that prepares the real-time respirable aerosol monitor before the actual application. An effective field calibration in some workplaces can reduce the need to correct the data for each session. However, the effectiveness of the field calibration may be limited because of the potential variability of the aerosol in the workplace and of the monitor in time, along with the effect of many other variables on the response of the monitor.

The correction factor, as a post-analysis, can be applied only to the session under investigation. If the correction factors calculated after many independent sessions are consistent, then the user should consider adopting a field calibration for that monitor and application. The calculation of the field-calibration factor is a more complex process, but it can be applied to several sessions assuming its validity. The application of the same field-calibration factor to multiple monitors of the same type depends on the intra-unit variability of the monitor type, which should be verified by the user. Establishing a field calibration or correcting the data from each session can be time- and resource-consuming. However, it is an important step because the calculation of a correction factor or the field-calibration factor can increase the accuracy of the data from the real-time respirable aerosol monitors and, therefore, the general acceptability of the results.

The user should take a proactive approach of identifying the objective for using the real-time respirable aerosol monitor and the specific application. As presented in other sections of the chapter, for some applications, the accuracy of the measurement is more important than for others. In those cases, the user should invest the time and resources in correcting the data or establishing a field calibration. Once the user decides that correcting the data or establishing a field calibration is necessary, the following best practices should be considered.

a. Reference data

Data points generated by a reference analysis should be used to assess the accuracy of the measurements from a real-time monitor. This process can lead to the calculation of a correction factor or the creation of a field calibration. Considering the target is respirable aerosol mass concentration, the reference method must be an established analytical method, such as NIOSH Method 0600, "Particulates Not Otherwise Regulated, Respirable" [NIOSH 1994]. There are two options for collecting respirable aerosol samples as a reference: 1) samples collected on the filter media housed inside the monitor and 2) samples collected side by side with filter-based samplers. In both options, appropriate filter media should be used, as indicated in NIOSH Method 0600, and the filter media must be preweighed before sampling.

If the monitor does not have an internal filter media, aerosol samples should be collected with side-by-side samples with filter-based respirable samples and real-time respirable aerosol monitor. The selection of the respirable filter-based sampler used to collect the reference sample is important. The user should consider the samplers listed in established analytical methods [NIOSH 1994]. If possible, the user should use the same respirable size selector used by the real-time respirable aerosol monitor to minimize inherent differences generated by different respirable samplers. If this is not possible, the user should ensure that both the monitor and the filter-based sampler operate at the optimal flow rate for each preselector.

b. Setup of the real-time respirable aerosol monitor

Refer to the user manual for the specific monitor for setup of the real-time respirable aerosol monitor. The user should understand and learn the specifics and characteristics of the monitor used. Particular attention should be given to the use and maintenance of the preselector, the flow rate of the pump, and the use of the proper particle transport line. Before any testing, the user must zero the monitor per instrument manufacturer guidelines. Zeroing the monitor by itself is not calibration—zeroing is the first step of the process and is needed to establish a baseline when no respirable aerosol particles enter the monitoring sensor. Zeroing is done by connecting a small in-line zero filter, supplied by the manufacturer, to the sampling line or to the monitor.

c. How to conduct testing for correction factor and field calibration

While theoretically the determination of the correction factor and the field calibration are different processes, the testing involved is quite similar. The testing is performed by simultaneously collecting the real-time respirable aerosol monitor data and the reference sample in a work environment. We advise conducting the field calibration in the same environment, while a realistic activity (i.e., drilling, blasting, crushing, paving) is generating similar types of aerosol. Attention to the environment is particularly important when mixed aerosols are present, because each type of particle might have an effect on the response of the monitor.

The testing presents some challenges compared with testing in laboratory aerosol chambers. The possibility of aerosol spatial variability is one challenge. High spatial variability occurs when respirable aerosol mass concentration measured at different but nearby spatial locations exhibits substantially different values at any given time. To minimize the effect of the spatial variability, the user should consider using multiple filter-based samplers and place them side-by-side near the real-time monitor. This is important especially for environments with high ventilation velocities, substantial cross-drafts, and multiple or mobile aerosol sources. Data obtained from the multiple filter-based samplers can then be used to determine the correction and/or field-calibration factor. If the filter media is used inside the real-time monitor, spatial variability is not a concern. In determining a correction factor from a field-calibration perspective, the only spatial variability of interest is between the reference measurement and the sensor.

Another factor to consider is the respirable aerosol concentration level. For field calibration, the testing should use realistic conditions. The user should calibrate the monitor in the field with the aerosol of interest at the concentration levels typical of the workplace. This can be accomplished by monitoring the worker or activity of interest while in operation. Attempting to increase the concentration level to collect more aerosol during the field calibration, or in a shorter period of time, can create unrealistic conditions in terms of aerosol characteristics and negatively affect the field calibration and worker's health.

While for the determination of the correction factor, the sampling time is defined by the monitoring activity, during a field calibration testing, the duration of sampling can be adjusted and optimized. The duration should account for the amount of aerosol mass collected for the reference analysis, whether inside the monitor or by filter-based samplers. The amount of mass collected should be well above the limit of quantification (LOQ) of NIOSH Method 0600 provided by the specific analytical laboratory. Generally, even in a dusty environment, several hours of sampling and monitoring are needed to collect a sufficient mass of dust. Filter-based samplers and real-time respirable aerosol monitors should operate simultaneously.

The focus of the testing is to ensure that the monitor data and the reference sample represent the same aerosol. In the case of fumes and mist, it is possible, due to vapor pressure, that organic and inorganic compounds will evaporate while the filters are stored for laboratory analysis. However, the real-time monitor will detect them in the atmosphere. In this case, the monitor response and the reference sample do not exactly represent the same aerosol, which could lead to differences between the results. For this reason, the user should be aware and knowledgeable of the potential volatility of the aerosol present in the workplace.

Finally, in the case of field calibration, because of the variability of the field conditions, it is good practice to repeat the process for a series of independent tests. A test is considered independent when the results are not affected by the conditions of another test. This can be accomplished by bringing the monitor back

to a clean environment, zeroing the instrument, checking the flowrate, and performing cleaning practices as indicated by the manufacturer. The same should be done for the reference filter-based samplers, if used. A user might want to know how many independent tests are needed to conduct a field calibration. The number of independent tests depends on the variability of conditions in the workplace. To assess this variability, a minimum of three tests should be considered. More than three tests may be needed for highly variable aerosol concentrations.

d. Calculating the correction or field-calibration factors

The calculation of a correction or field-calibration factor aims at increasing the accuracy of real-time respirable aerosol monitors. In the case of field calibration, each independent testing is a stand-alone set of results that can be used for the calculation of the factor. The first step in the analysis is reviewing the results from the reference samples. The user should be cautious using any data below the LOQ, as indicated by the analytical laboratory. A result below the LOQ indicates the laboratory does not have the same level of confidence as it does in the values above the LOQ. Therefore, the user should consider discarding all the values below the LOQ. All the values above the LOQ from the reference filter-based samplers for one independent testing should be 1) converted into a respirable mass concentration and 2) averaged to obtain a reference point for one test. The range of the values should give the user an indication of the spatial aerosol variability around the monitor of interest during each testing.

The second step in the analysis is to retrieve the mean mass concentration value from the monitor for each single independent test. Each mean mass concentration value from the real-time monitor should be matched with the corresponding averaged mass concentration value calculated from the reference samplers. The ratio between these two values is the factor determined for that specific independent test. The factor is used to transform the measurement of the real-time respirable aerosol monitor into the averaged value obtained by the traditional samplers. In the case of a correction factor, the process ends at this point.

In the case of field calibration, if multiple independent tests were conducted, the final step is averaging the factor values from the different tests. If there is a sufficient number of multiple sessions, or if there is concern of performance variability across concentration ranges, other data processing approaches, such as a regression analysis, can be performed. This step will provide the final factor of the field calibration. The user should pay attention to the range of correction factor values calculated for each testing. If the range is within 10%–15% of the average, the conditions for the different tests may be considered consistent. Unfortunately, it is possible for some monitors to generate a range much higher than 15% even with consistent conditions. In that case, the user should refrain from developing a field-calibration factor. If more accurate results from the monitor are needed, the user should consider calculating a session correction factor for each session. The acceptable range should be defined by the user's professional judgment.

e. Verifying the validity of the field-calibration factor

Once the field-calibration factor is established, the user can consider it a parameter in the software to set up the monitor or use it to correct the data of the real-time respirable aerosol monitor during its subsequent operation. The verification test is identical to a single field-calibration test described above. However, the data of the real-time respirable aerosol monitor are already corrected by the calculated factor used in the monitoring setup or during post-analysis. After a verification test, if the factor is adequately effective, the average concentration measured by the traditional samplers and monitor should be similar: a difference of 15%–20% can be considered acceptable. However, a large relative difference (50% and larger) can occur, resulting from different factors.

Changes in environmental conditions and type of aerosol can influence the field calibration. The performance of a single instrument might shift in time, requiring the user to verify the field-calibration factor and adjust it if needed. The acceptable difference needs to be defined by the user based on the application and on their professional judgement, for example, if the real-time respirable aerosol monitor is used in a different environment and/or the aerosol conditions have changed. The user should consider establishing factors for each area of interest and possibly revising the field-calibration factor periodically. As good practice, the user should conduct verification of the field-calibration factor periodically. The frequency for revising these factors should be set based on the frequency of monitor use. If a monitor is used rarely, like once a quarter, and if it is properly stored and maintained, the field-calibration can be revised twice a year. If the monitor is used more often, the user can use their professional judgement to decide how often the verification needs to take place. The frequency for revising these factors can be adjusted on the consistency of the factors—if a factor does not change substantially in time, the frequency can be lower. The determination of the quality of the corrected real-time respirable aerosol monitor data is at the discretion of the user. The relative difference should be low, indicating that the data is similar to the reference analysis in terms of mass concentration for respirable aerosol.

Finally, it is important to acknowledge that NIOSH and other national and international organizations are involved in discussions and activities related to the real-time monitors' measurement uncertainty, interunit variability, uncertainty budgets, and temporal precision. Some of the most updated established concepts on this topic can be found in Chapter UA [NIOSH 2014b] and in articles in peer-reviewed journals. We refer the reader to those discussions, as that is beyond the scope of this chapter. This chapter was created to fulfill the need for a user to properly select, set up, and implement the use of a real-time respirable aerosol monitor in the field.

4. Applications

Real-time respirable aerosol monitors can be useful tools for industrial hygienists and health and safety professionals for a variety of activities and tasks. Before using a real-time respirable aerosol monitor, a

user should first identify the objective of the activity and how the data generated by the device will help to create new information and knowledge. This first step is common for the use of any direct reading and real-time sensing technology and an important part of the "Right Sensors Used Right" approach established by the NIOSH Center for Direct Reading and Sensors Technologies. More about this approach is provided in the NIOSH Science Blog [Cauda and Hoover 2019].

The use of real-time monitors can be helpful, for example, to assess the effectiveness of interventions [Colinet et al. 2018; Johnson et al. 2017; NIOSH 2019; Patts et al. 2019], such as engineering control technologies and work practices. The use of the monitors has also been found effective in engaging and empowering workers to induce and implement change because most monitors have a display that the worker can view periodically during the shift to assess the respirable aerosol mass concentration. In this way, the worker is more involved in the monitoring process. This effect, associated with the concept of risk communication, has been studied in-depth in relation to the use of real-time respirable aerosol monitors [Haas et al. 2016].

Possible specific applications for real-time respirable aerosol monitors in the workplace include these:

a. On-site determination of any type of time-weighted average respirable aerosol concentration.
b. Investigation of events/tasks with high concentration levels.
c. Analysis of concentration levels above a threshold value.
d. Identification and analysis of stand-alone periods within a monitoring event.
e. Analysis of the concentration evolution over time within a monitoring event.
f. Comparison of different monitoring sessions.

Each application is briefly described below in terms of overall objective, how the data from the monitor can be treated and used to accomplish the objective, and limitations associated with the application.

a. On-site determination of time-weighted average respirable aerosol concentration

A user might need to obtain information about the exposure of a worker (personal monitoring) or the concentration in a specific area of the worksite (area monitoring), over a period of time, immediately at the end of the monitoring event. This need can be associated, for example, with an urgency to assess a certain work practice or the effectiveness of a control technology. This supports the idea of using direct-reading methodologies rather than analytical laboratory techniques. A real-time respirable aerosol monitor can be used to determine, on-site, the average respirable aerosol concentration relative to a monitoring event by averaging the real-time data for the entire session (Figure 1) as soon as it has been exported from the monitor. In this way, the user does not need to wait for the analytical laboratory to analyze respirable aerosol samples gravimetrically.

The user should be aware of the limitations of real-time respirable aerosol monitors to generate accurate results when monitoring different types of aerosol. The average respirable aerosol mass concentration determined with data from a real-time monitor can either overestimate or underestimate the true value. To reduce the effects of this limitation, the user should consider analyzing the internal filter gravimetrically, if available, to correct the direct reading results from the monitor. If the monitor does not have a filter, a side-by-side paired respirable aerosol sample should be collected and analyzed gravimetrically. In both cases, the correction can be done once the analytical laboratory reports the results. Alternatively, a user can consider calibration in the field using the real-time monitor with a procedure described in the section "Correction and field-calibration factors" above.

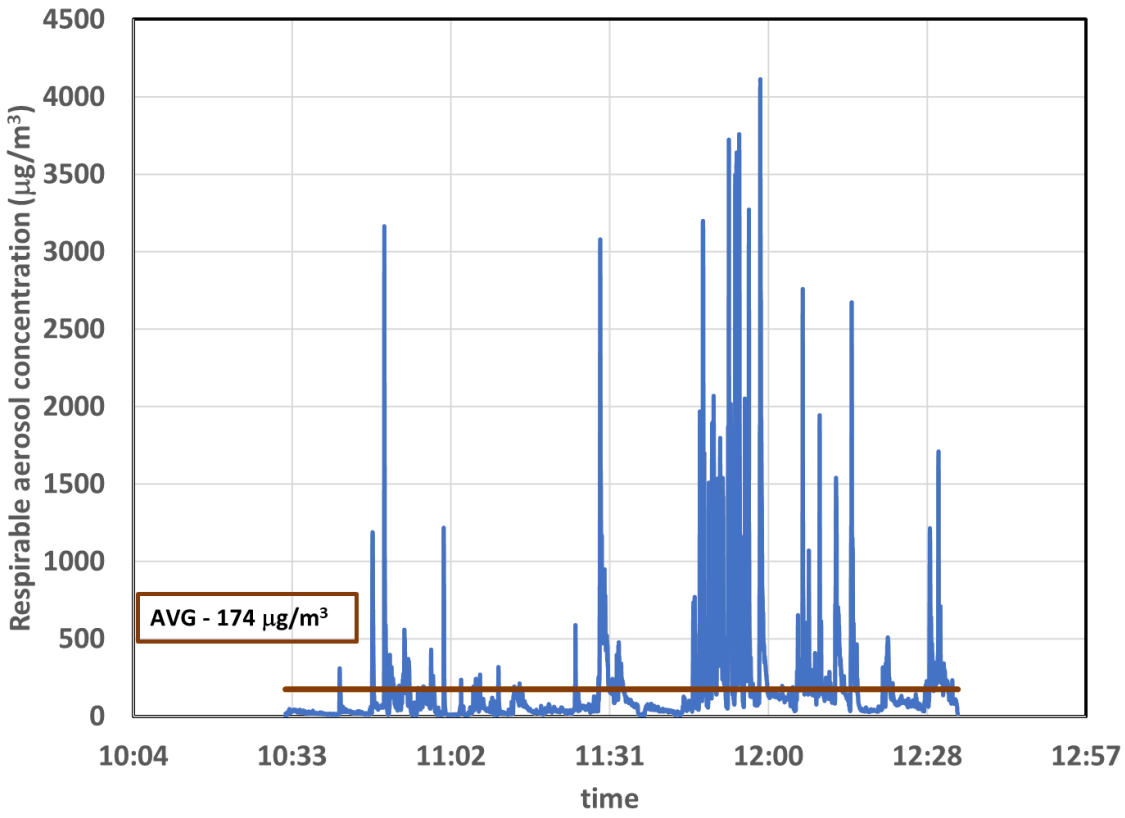

Figure 1. A single real-time respirable aerosol monitor session with the time-weighted average aerosol concentration calculated.

b. Investigation of events/tasks with high concentration levels

One of the most recognized benefits of using a real-time monitor is the ability to analyze specific events within a period of time (Figure 2) or the entire shift; this capability is helpful in evaluating work tasks,

specific sources, and/or activities. The response time of the monitor is important here especially if the task duration is short. Often, the user is interested in events characterized by an unusually high intensity reading for the measured value, which, in the case of this chapter, is respirable mass concentration level. Real-time respirable aerosol monitors are particularly suitable for this application because of their quick response time and the capability to quickly assess the variability in mass concentration. The identification and classification of events of interest can be done by setting up one or more logic rules; for example, an event can be classified as high concentration if the intensity is higher than a certain value or threshold. The user can also analyze the intensity in terms of mass concentration and duration of these events, however, they must remain aware of possible bias in the measurement of each single datapoint in a set. The comparison of different events can help with prioritizing interventions, engineering controls, and work practices.

The analysis of high mass concentration events can be facilitated with the simultaneous use of video recording. This concept was explored by NIOSH in the 1990s [NIOSH 1992] and used in the NIOSH Helmet-CAM system [NIOSH 2014a] with the NIOSH EVADE software. Synchronizing the data from the real-time respirable aerosol monitors and recording a video provide critical contextual information from the workplace relative to the specific events of interest. Without tools like the NIOSH EVADE software, the user should make notes of time and task/process observations (traditionally called a time study).

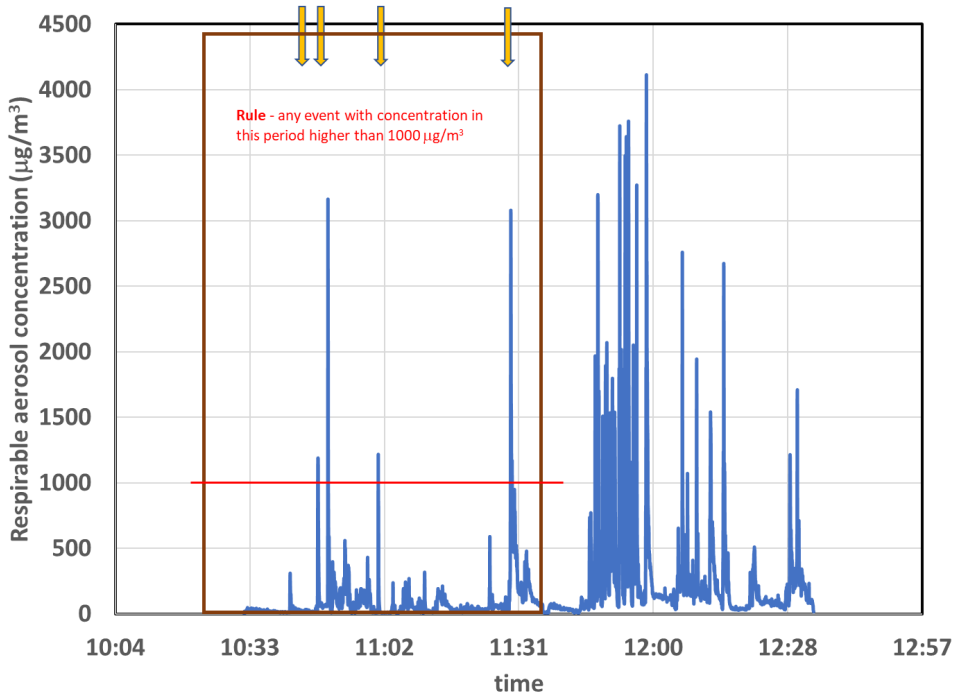

Figure 2. A single real-time respirable aerosol monitor session with high concentration events highlighted (arrows).

c. Analysis of concentration levels above a threshold value

The dataset from a single session of a real-time respirable aerosol monitor can be analyzed to evaluate the percent of time the mass concentration levels exceeded a certain value or threshold. In terms of thresholds, a user could consider using an occupational exposure limit (OEL), such as a NIOSH recommended exposure limit (REL), an OSHA/MSHA permissible exposure limit (PEL), or an action level often half of the REL and PEL. The user should consider that the thresholds would only represent estimates of the thresholds because of issues related to the accuracy of real-time respirable aerosol monitors. Other levels meaningful to the user can be selected to extract valuable information from a single session. A meaningful level can be, for example, a mass concentration equal to the baseline multiplied by a certain factor. The baseline can be defined as the average value reported by the real-time monitor when no evident aerosol was present in the environment.

The analysis can investigate the fraction of the data (%) that showed a mass concentration level higher than this meaningful level. In Figure 3, the analysis calculated the fraction of time during which the concentration was 3 times and 10 times higher than the baseline. The factors are at the discretion of the user, and they should be selected based on the objective of the analysis. The data processing for this application might require the identification of a baseline for the single session. It is not a straightforward determination, and the user should exercise professional judgment, as well as knowledge of the workplace, for this baseline determination. Once the baseline and the threshold are identified, a few logic formulas can be applied to the dataset to obtain the information in terms of percent of time.

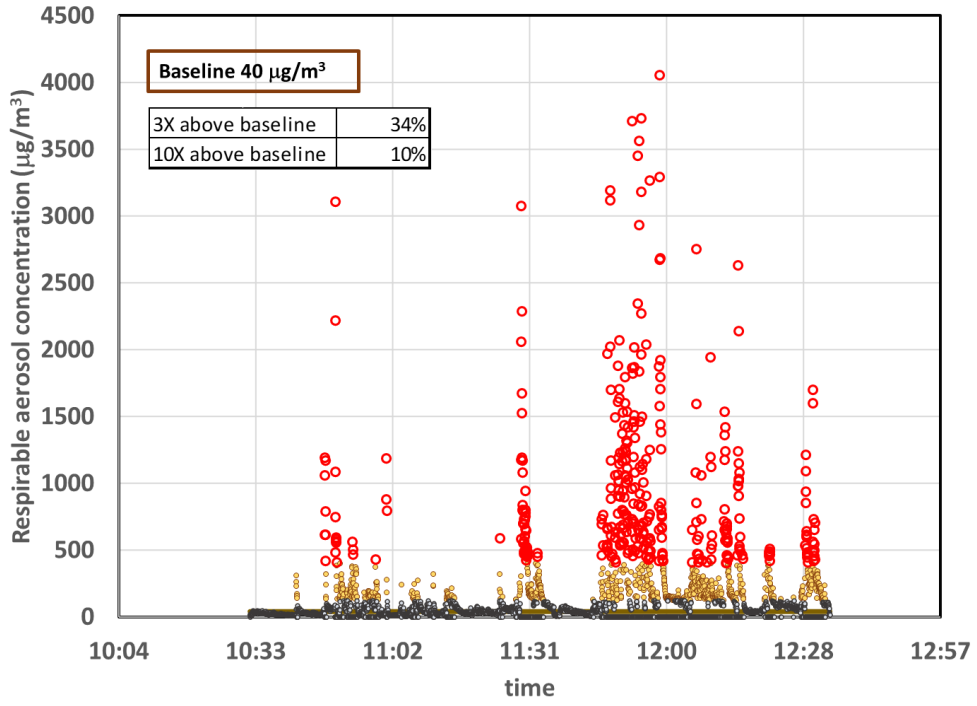

Figure 3. A single real-time respirable aerosol monitor session with the data color-coded based on two concentrations (3x and 10x above baseline).

d. Identification and analysis of stand-alone periods within a monitoring event

By using contextual information associated with a single real-time respirable aerosol monitor session, a user might decide to split the session into two or more stand-alone periods. This can be the case, for example, when there is an interest to investigate independently different tasks during a shift. Another possibility is the occurrence of a critical event, such as the failure of engineering control technology, and the user intends to compare the data before and after the event. Once the data are divided, descriptive statistics, such as arithmetic mean, geometric mean, standard deviation, or geometric standard deviation, can be applied to each period (Figure 4). The comparison of the basic statistical results can provide information on the influence of each stand-alone period to the entire sampling event. Although it is still important to be aware of the bias of the values reported by the real-time monitor, this application can be helpful for the prioritization of the interventions aimed at minimizing the average concentration levels. Also important to consider is that the division of a session into multiple stand-alone periods does not alter the original dataset, but it creates an additional layer of interpretation of the results.

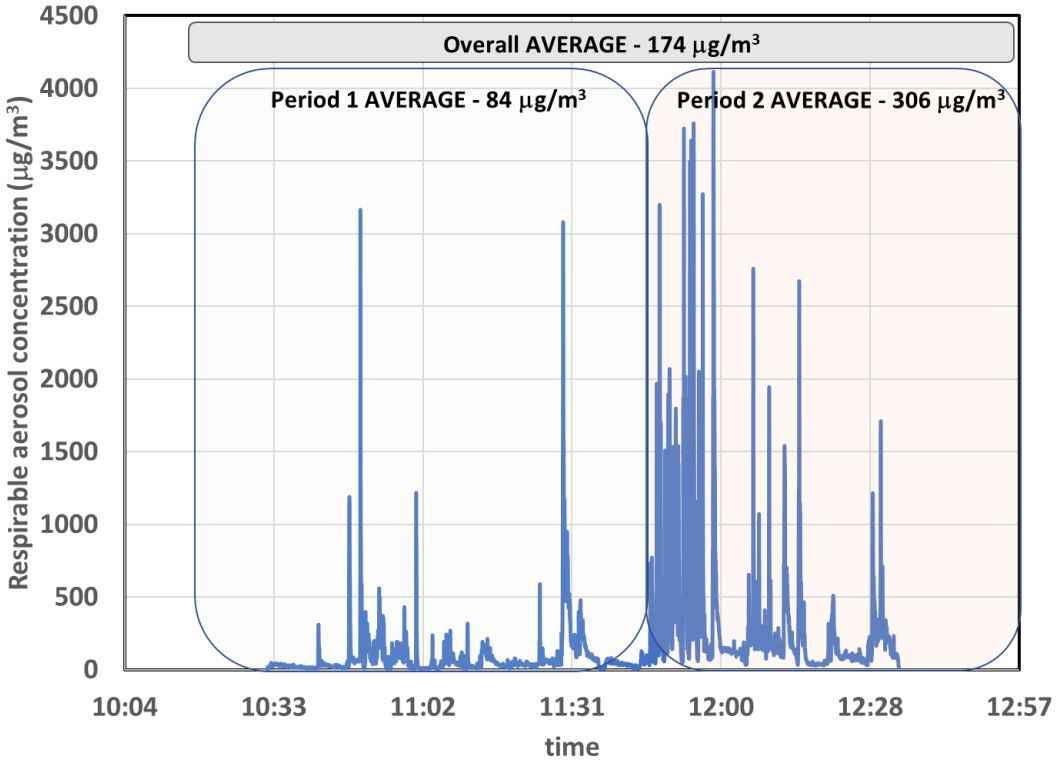

Figure 4. Session organized in two stand-alone periods.

e. Analysis of the concentration evolution over time within a monitoring event

The evolution in time of the respirable aerosol concentration levels and their variability during an entire monitoring session can be analyzed to assess evident trends and patterns. The application can provide the user with valuable information on how the respirable mass concentration progresses during the sampling event and/or shift. This application can help users to identify situations when a process is going out of control, using the measurement in conjunction with quality control engineering charts. The evolution might not be immediately apparent simply by observing the data. This analysis can be done in different ways. One approach is calculating a moving average that is constantly adjusted by new datapoints collected in time. Another approach is the calculation of average concentration levels for short 15-minute periods of time (Figure 5). By parsing an entire session into 15-minute periods, it is possible to more clearly appreciate whether, during the sampling event, the respirable aerosol mass concentration increased or decreased with time. At the same time, by calculating the standard deviation for the 15-minute data subsessions, how the variability in the data evolved in time will be more evident. Two 15-minute periods can be characterized by the same average concentration but with a different standard deviation, which is indicative of the variability of the concentration. For

this application, the user should also be cautious of the accuracy of the datapoints from the real-time respirable aerosol monitor.

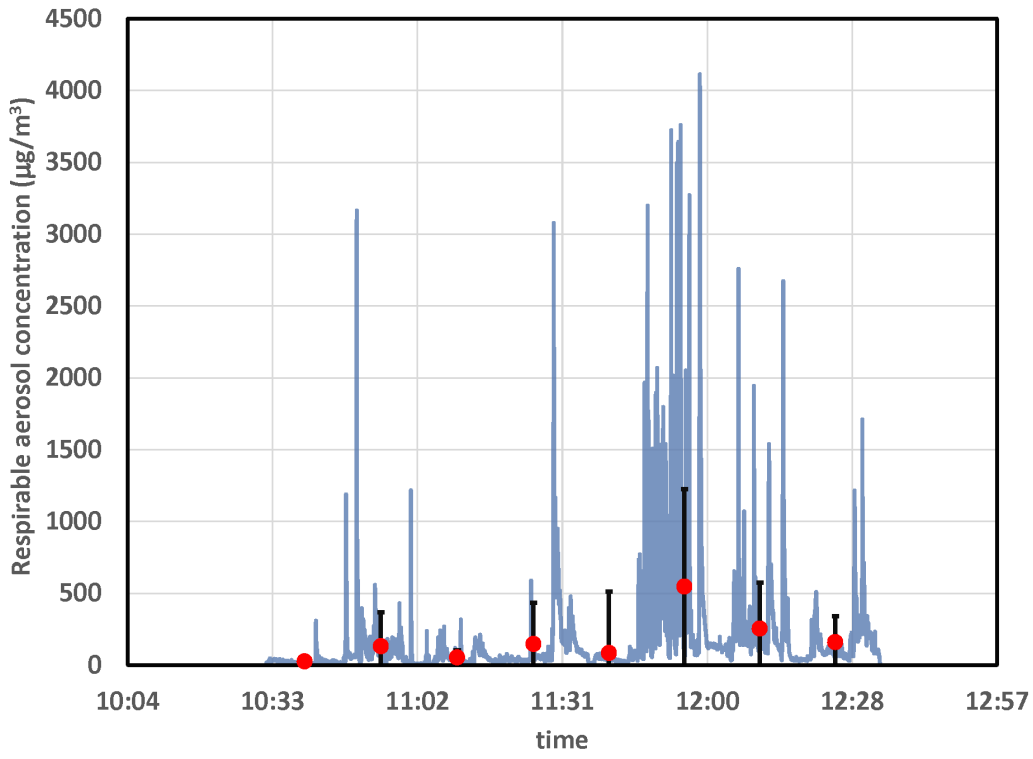

Figure 5. Analysis of the session with 15-minute average levels (red dots) and standard deviation (bars).

f. Comparison of different monitoring sessions

The dataset for one session can be plotted for comparison with other datasets (Figure 6) as a distribution or a box plot [Patts et al. 2020]. This comparison can help evaluate similarities and differences for the same location/worker—like Worker A as seen in Figure 6—on different days or to compare different locations/workers. When plotting entire datasets for this application, a user should first determine whether the data are normally or log-normally distributed. If the data are log-normally distributed, geometric mean and geometric standard deviation should be determined, and they can be used as additional statistical metrics. When comparing different datasets, the user should be aware of the issue of autocorrelation: autocorrelation is present when different datapoints in a dataset are not completely independent measurements. In the case of a real-time respirable aerosol monitor session dataset, each datapoint collected at a certain time can be correlated to other datapoints present in the same dataset. This phenomenon breaks one of the rules of independent measurements needed for several statistical techniques, such as analysis of variance (ANOVA). A technique has been proposed to resize each dataset to minimize this issue [O'Shaughnessy and Cavanaugh 2015]. When several

sessions are compared, the analysis can provide a visual representation of the variability of the mean and standard deviation for different sessions. Therefore, the assessment of the evolution of the respirable aerosol mass concentration levels in time and/or space is possible. Also, in this case, the user should decide to adopt a log-normal representation of the data and consider differentiating the data that have been corrected using a time-integrated sample or data from a calibrated monitor.

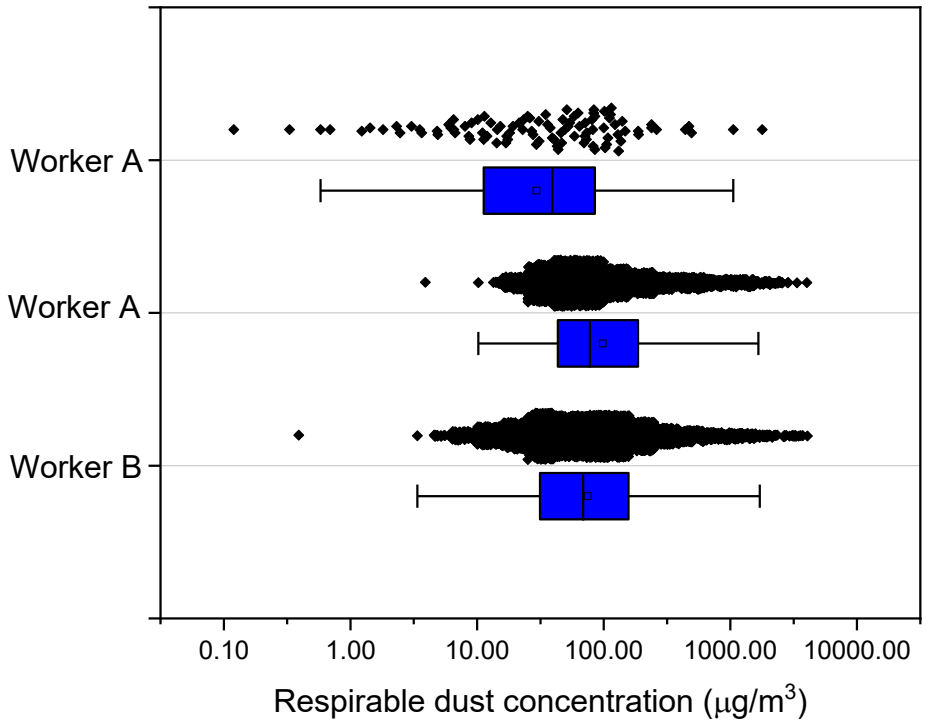

Figure 6. Comparison of datasets collected by real-time respirable aerosol monitors. Each datapoint in the set is plotted individually together with the boxplot representative of the entire session. For each box, median (empty box), geometric mean (line), 25%–75% quartile interval (box), and 1.5 standard deviation (whiskers).

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