Direct-reading methods for workplace air monitoring☆

Direct-reading methods (DRMs) are valuable tools for detecting and measuring worker exposure to inhalation hazards. A DRM can be either a device or instrument capable of measuring gases and vapors and aerosols such as dusts, fumes, and mists without manipulation of the sample by the user or sending the sample to an offsite laboratory. Devices are those DRMs that are simple, single point in time measurement of exposure. Instruments are DRMs that contain a sampling system, signal-processing electronics, a display system, and a detector. This manuscript will describe the DRMs which may be used to evaluate worker exposure to gases, vapors, and aerosols. The manuscript will also discuss factors to consider when selecting a DRM and recent developments and events related to DRMs.

By Christopher C. Coffey, Terri A. Pearce

INTRODUCTION

Direct-reading methods (DRMs) are valuable tools for detecting and measuring worker exposure to inhalation hazards. For the purposes of this discussion, DRMs are defined as either a device or instrument capable of measuring gases and vapors or aerosols such as dusts, fumes, and mists without manipulation of the sample by the user or sending the sample to an offsite laboratory. Devices are those DRMs that are simple, single point in time measurement of exposure. They can be passive or active and quantitative or qualitative.

Instruments are DRMs that contain a sampling system, signal-processing electronics, a display system, and a detector. Many operate on self-contained battery power but some also use, or may require, line current. The instrument detector or sensor is a component that converts a characteristic property of the contaminant into an electrical signal.

Direct-reading methods provide on-site measurement regarding the exposure of interest that can then be utilized to ascertain the potential degree of health or safety risk associated with that exposure. These methods may also be utilized to determine the efficacy of any control measures (e.g., environmental controls, etc.) that have been designed to reduce exposures at the facility. They have several advantages over conventional methods (e.g., charcoal/thermal desorption tubes, gravimetric sampling, etc.) for assessing worker exposure. They provide immediate results on-site without having to store and ship samples. With DRMs and their ability to collect short samples, work practices can be modified while the exposure is occurring. Instruments have the ability to log large amounts of data for later analysis.

Direct-reading methods may be used for area, process, or personal monitoring. Direct-reading methods can be either nonspecific and/or specific to the contaminant of interest depending up the type of detector used. It is convenient to describe four groups of DRMs: personal – designed to be worn by an individual; portable – hand-held or easily carried using handles or shoulder straps; transportable – requiring a cart or other support for movement to or from the monitoring site; and fixed position – permanently installed at a specific location. Most of the DRMs used for workplace exposure assessment are of the portable and personal type. Therefore, this discussion will focus mainly on these two types of DRMs presenting an overview (i.e., a description, an explanation of the principle of detection, and a brief discussion of instrument application, including capabilities, restrictions, and limitations).

GAS AND VAPOR METHODS

Colorimetric Devices

Colorimetric methods rely on color change to determine the concentration of chemicals in the air. There are two categories of this type of method: detector tubes using a pump for short-term (grab samples) and long-term exposure measurements and passive dosimeters. Tubes are length of stain devices where concentration is

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related to the amount or length of reagent discolored or color intensity where concentration is related to the degree of color change as compared to a standard. Some advantages of these devices are: low cost, ease of use, and the availability for a range of gases and vapors. All colorimetric monitors have temperature, relative humidity and ambient pressure limitations due to a chemical reaction being involved. Other limitations include the interpretation of the length of the stain or the change in color intensity or tint.

Active

Colorimetric tubes, also known as detector tubes are length of stain monitors. Colorimetric tubes are available for both short- and long-term sampling, meaning upwards of 8 hours. Their operation is relatively simple. Once a tube is selected for the chemical to be measured, the ends are broken off the tube using the tool provided. The tube is inserted into the pump housing (either hand for short-term sampling or motor driven for longer-term sampling). A hand pump is either squeezed a specific number of times or the handle is pulled on the piston a specific number of times (Figure 1). A motor driven pump is allowed to pull air through the tube for a predetermined time. Colorimetric tubes are available to measure over 500 different gases and vapors.[1] Tolerances on the accuracy can be, in some cases, 25–30%. Selection of the best tube model involves; identifying the best measurement range to use, using the right support equipment (e.g., sample container, connective hardware and pump), and drawing the correct amount of contaminated air through the tube. Some tubes will cross-react with other chemicals which, if present, may result in a false or misleading reading. Colorimetric tubes should not be used beyond their expiration date.

Passive

Long-term tubes

Long-term sampling can also be conducted using diffusion tubes which work by passive gaseous diffusion and can be used over a period of 8 hours or longer. If the chemical is present, the material inside the tube changes color and the length of the color stain is read against the scale on the tube to give the concentration. Originally, designed as a personal monitor, the diffusion tubes also can be used for area monitoring. The time-weighted average can be calculated at any time during the measurement by simply dividing the length of the tube reading by the elapsed sampling time (in hours).

Spot plate badges

Spot plate badges are another type of passive colorimetric method. They are designed for visual evaluation and contain a button or indicator strip that changes color when a critical amount of the target gas/vapor is reached.

Figure 1. Colorimetric tube with manual pump for short-term measurements. *Photograph courtesy of Draeger Safety Inc.*

Instruments

Gas and vapor monitoring instruments are commonly used in confined space monitoring and emergency response. The most common detectors found in these instruments are based on galvanic, thermochemical, electrochemical, and spectral chemical among others. Many of these detectors are capable of responding to nanogram (10^{-9}) quantities of analyte, and some reach as low as picogram (10^{-12}) levels. The operating principle of each type of detector will be described along with the gases and vapors it can detect and any limitations.

Galvanic

A galvanic detector is used to measure the amount of oxygen present in the workplace. It uses a high surface area metal-catalyzed gas diffusion electrode. Upon reaching the catalyst surface exposed to the electrolyte, the oxygen reacts generating a signal which is proportional to the partial pressure. The galvanic detector has reduced susceptibility to particulates but should not be used at high temperatures.[2] They are insensitive to shock and vibration. As the sensor ages, a loss of sensitivity may occur, making periodic recalibrations necessary. If exposed to very high levels of oxygen, the sensor may need a long time to recover from this "oxygen shock".

Thermochemical

Gases and vapors have certain thermal properties that can be exploited in their analysis.[3] Thermochemical instruments for industrial hygiene applications measure either thermal conductivity or catalytic.

Thermal conductivity

Thermal conductivity detectors (TCDs) are relatively simple devices that operate on the principle that a hot body will lose heat at a rate that depends on the composition of the surrounding gas (Figure 2). That is, the ability of the surrounding gas to

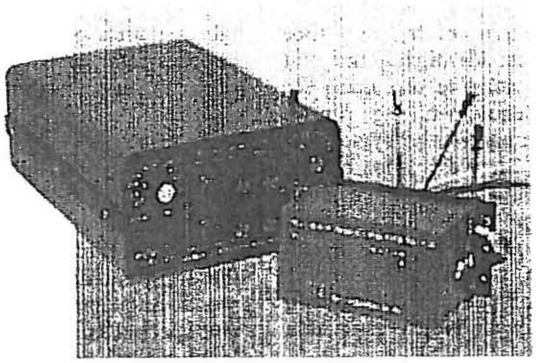

Figure 2. Thermal conductivity detector.
Photograph courtesy of VICI Valco Instruments.

conduct heat away from the hot body can be used as a measure of the composition of the gas. TCDs are universal detectors, responding to all compounds. They cannot distinguish between different gases. TCDs are also used in the analysis of permanent gases (argon, oxygen, nitrogen, carbon dioxide) because they respond to all these pure substances. TCDs have large linear dynamic ranges, on the order of 10^5, and limits of detection on the order of 10^{-8} gram of solute per mL of carrier gas (10–100 ppm for most analytes). TCDs are good general purpose detector for initial investigations with an unknown sample. They require good temperature and flow control. They have a long detector life and are easy to use. TCDs are not as sensitive as other detectors but they are non-destructive.[4]

Catalytic

Catalytic (heat of combustion or electrocatalytic) detectors are single-point detectors and are generally, nonspecific universal detectors. These detectors are used to monitor for combustible gases (e.g., methane, ethane, propane, butadiene, among others). Some specificity can be introduced by controlling the combustion temperature so that it is insufficient to burn interfering gases and by careful selection of the oxidation catalyst. More specific detectors are available for carbon monoxide, ethylene oxide, hydrogen sulfide, methane, and oxygen deficiency. They are low cost, simple to operate, have a good lifespan, and are approved for use in hazardous atmospheres. Their limitations include: non-specificity, easy poisoning of the detector, limited range of gases, and low sensitivity. Most of these instruments read out in terms of percent of the lower explosive limit (LEL) or hundreds of ppm, and the detection limits are analyte dependent.

Electrochemical

Electrochemical techniques involve the measurement of electrical signals associated with chemical systems.[5,6] These chemical systems are typically incorporated into electrochemical cells containing an electrolyte. Sensor operation depends on changes in electrical signals at two electrodes inside the cell due to oxidation–reduction reactions of the gas or vapor at the electrodes. Electrochemical techniques include instruments that operate on the principles of conductivity, potentiometry, coulometry, and ionization. They have good sensitivity, wide measurement range, and low power requirements and cost. They are non-selective, are affected by other gases, and have a restricted temperature range.

Conductivity

Conductivity instruments are primarily used for detection of corrosive gases, e.g., ammonia, hydrogen sulfide, and sulfur dioxide. They are most effectively used in isothermal environments at or near room temperature and with few potentially interfering compounds. Chemical prescrubbers may be required to remove interfering compounds. They have high selectivity and sensitivity, are easy to operate and can be used in rugged field conditions. They have a high initial cost. Mercury detectors are a special form of conductivity detection. In these instruments, a gold film is utilized to amalgamate the mercury which changes the resistance of the film. This change in resistance is measured to provide the concentration of mercury. The gold film requires regular cleaning.

Potentiometry

Potentiometry is defined as the measurement of the difference in potential between two electrodes in an electrochemical cell under the condition of zero current. Gases and vapors can react with reagents, affecting an oxidation/reduction, the extent of which is proportional to the concentration of the reacting gas. Whereas potentiometry is basically a nonspecific technique, some degree of specificity may be obtained through the selection of the membrane through which the gaseous analyte must diffuse to enter the electrochemical cell, the selection of the reagent, the specific potential range, and the type of electrodes used. Potentiometers are used for the measurement of a variety of contaminants including carbon monoxide, chlorine, formaldehyde, hydrogen sulfide, oxides of nitrogen and sulfur, oxygen, and ozone (Figure 3). These instruments perform best at or near room temperature.

Coulometry

Coulometric analyzers determine the quantity of electricity required to affect the complete electrolysis of the analyte of interest. The amount of electricity required is proportional to the amount of analyte present. The analyte may be the contaminant itself or a chemical with which the contaminant reacts quantitatively. Coulometry is free of temperature dependencies and inherently very accurate. Judicious choice of filters, membranes, and electrolytes can be used to improve specificity. The vast majority of these instruments are configured as oxygen or oxygen deficiency monitors, although coulo-

Figure 3. Electrochemical analyzer which uses potentiometry.
Photograph courtesy of Interscan Corporation.

metric analyzers are also available for carbon monoxide, chlorine, hydrogen cyanide, hydrogen sulfide, oxides of nitrogen, ozone, and sulfur dioxide.

Ionization

There are three types of ionization detectors: flame ionization (FID); photoionization (PID); and electron capture (ECD). All rely on the ability of their respective energy source–flame, lamp, or radioactivity–to ionize the species of interest.

Flame ionization

The FID is a very sensitive detector for organic compounds and excellent in trace analysis (Figure 4). Flame ionization is a nonspecific detection method for most organic compounds, but response is best for hydrocarbons. Molecules that contain "heteroatoms" such as oxygen reduce the detector's response. A FID does not respond, or is not very responsive, to common constituents of air, including water vapor, carbon monoxide, carbon dioxide, sulfur dioxide, and oxides of nitrogen. Compounds containing electronegative elements such as halogens and sulfur depress the response. FIDs work well as portable survey instruments that are suitable for a wide range of measurements. They have a long detector life and are easy to use. Because their operation requires a flame, they should not be used in combustible/ flammable atmospheres.

Photoionization

In a PID, the contaminant gas or vapor is ionized by an ultraviolet (UV) lamp of known, constant voltage (Figure 5). Molecules having ionization potentials less than the energy emitted by the lamp are ionized.[7] This photoionization generates a signal (current) at the collector which is proportional to the amount of ionized species. A PID can be somewhat selective through judicious choice of UV lamps of varying

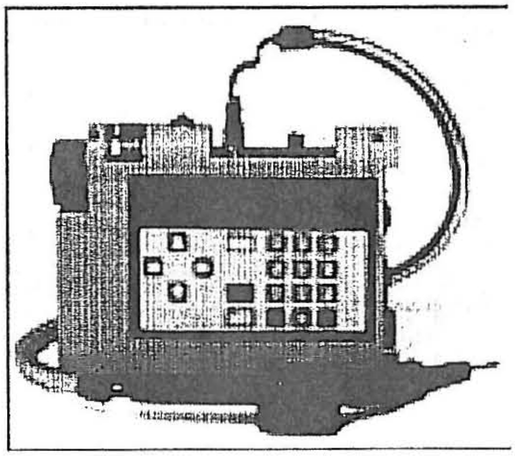

Figure 4. Combination flame ionization and photoionization instrument.
Photograph courtesy of Thermo Fisher Scientific, Inc.

Figure 5. Handheld PID detector.
Photograph courtesy of RAE Systems.

energies. Most PIDs have only one lamp, but lamps can be exchanged depending on the compound selectivity required. Compounds routinely analyzed by PIDs include aromatic hydrocarbons, or heteroatom containing compounds such as organosulfur or organophosphorus species, as these compounds have ionization potentials within reach of commercially available UV lamps. They have some utility for inorganic compounds such as nitric and sulfuric acids, hydrogen sulfide, arsine, and phosphine. PIDs provide for continuous measurement, are easy to use/calibrate, and have a rapid response and good sensitivity. When using higher energy lamps, potential interference of water vapor or oxygen must be considered.[8]

Electron Capture

An ECD uses a radioactive beta particle (electron) usually nickel-63 to ionize a carrier gas. The ECD is very selective and highly sensitive in its response, particularly for halogenated compounds (e.g., pesticides, peroxides, compounds with nitro groups, conjugated carbonyls, and some organometallic compounds); it is also useful for sulfur hexafluoride. It is not sensitive to amines, alcohols, and hydrocarbons. They are relatively expensive but have a long detector life.

Spectrochemical

Spectrochemical instruments include infrared (IR) analyzers, ultraviolet and visible (UV–VIS) light photometers, chemiluminescent detectors, and photometric analyzers.[9] Photometric analyzers include fluorescent and spectral intensity detectors. In general, spectrochemical analysis involves the use of a spectrum or some aspect of a spectrum to determine chemical species. A spectrum is a display of intensity of radiation that is emitted, absorbed, or scattered by a sample versus wavelength. This radiation is related to photon energy via wavelength or frequency.

Infrared

Infrared spectrometry involves the interaction of the infrared portion of the electromagnetic spectrum (wavelength from 770 nm to 1000 μm or 12,900 to 10 cm^{-1} in wave number) with matter (Figure 6). Nearly all molecules absorb infrared radiation, making the technique widely applicable. Because the infrared spectrum of a given molecule is unique to that molecule, IR can be fairly specific and useful in compound identification. However, use of a single wavelength for measurement of analytes in an uncharacterized mixture is unreliable because of potential interference by compounds with similar absorption wavelengths. The user needs to be aware that certain ubiquitous compounds such as water absorb very strongly in the infrared. Caution must be exercised to avoid making measurements at or near these absorbances. If interferences are absent, they have good accuracy and a operating range from sub-ppm to a few percent. They are non-poisonable. They are expensive and relatively complex.

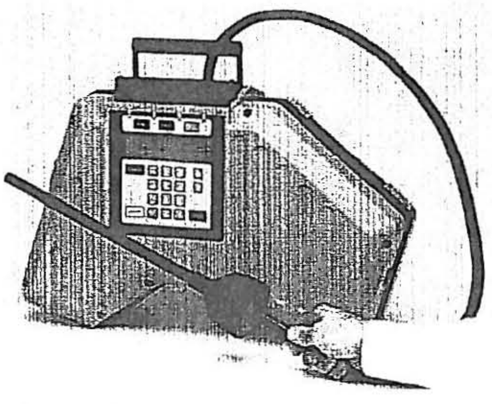

Figure 6. Infrared spectrophotometer.
Photograph courtesy of Thermo Fisher Scientific, Inc.

Ultraviolet-visible light

UV–VIS light photometers operate on the principle of absorption of electromagnetic radiation. The UV is that portion of the electromagnetic spectrum having wavelengths from 10 to 350 nm. The actual spectral range for direct-reading UV instruments is closer to 180–350 nm. The visible spectrum (350–770 nm) has longer wavelengths than the UV and correspondingly lower energies (1.6–3.6 eV). This type of instrument can be used as a continuous monitor for a variety of compounds: mercury, ozone, organic vapors, ammonia, sulfur dioxide, and oxides of nitrogen. Primarily used as area monitors, UV–VIS instruments are capable of detecting contaminants in the ppm range. Compounds with similar UV–VIS spectra act as interferences.

Chemiluminescence

Chemiluminescence is a form of emission spectroscopy wherein spectral information is obtained from nonradiational activation processes.[3] In this case, the emitted energy results from species that are excited by chemical reactions and are returning to a lower energy state by emission of a photon. The emission of photons from these excited electronic states is measured by a photomultiplier tube or solid state device. Chemiluminescence analyzers are primarily used for measurement of oxides of nitrogen, ammonia, and ozone. The presence of ethylene gas or products of its incomplete combustion may interfere. No other common pollutants are known to interfere, but water vapor can cause a positive interference that must be corrected for during instrument calibration. The instruments have a high degree of specificity and typical limits of detection on the order of 10 ppb. These analyzers are relatively expensive.

Photometric

This category includes fluorescence analyzers, flame photometric detectors, spectral intensity analyzers, and

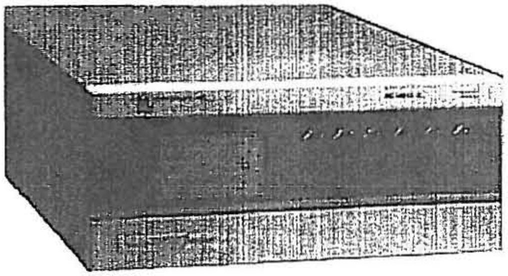

Figure 7. U.V. fluorescence sulfur dioxide analyzer.
Photograph courtesy of Envco Global Group of Companies.

colorimeters. The first three techniques are all examples of emission spectroscopy wherein the excitation process is radiative in nature.

Fluorescence

Fluorescence is the emission of photons from molecules in excited states that result from the absorption of energy from a radiation source. A narrow band of excitation and emission wavelengths can make the instrument very selective and often specific. Fluorescence is capable of detecting analyte molecules at extremely low concentrations (routinely one fluorescent molecule in a billion molecules). The fluorescence of a molecule is often sensitive to its local environment, which must be considered when calibrating the instrument. Fluorescence instruments are available for carbon monoxide, sulfur dioxide, sulfur (Figure 7) and phosphorous compounds, and halogenated hydrocarbons. Typical limits of detection are in the 5–10 ppb range.

Flame photometric

Flame photometric detectors (FPDs) can be adjusted to obtain selectivity for nanogram quantities of sulfur or phosphorous compounds. The detector works by measuring the emission of light from a hydrogen flame. With FPDs, calibration is critical because these detectors exhibit little or no linearity. FPDs have limits of detection in the low ppb range.

The pulsed FPD (PFPD) is a type of FPD which is based on a flame source and combustible gas flow rate that cannot sustain continuous flame operation. The PFPD is very selective because of the time domain information that it provides. Compounds containing rings of carbon and other atoms or species such as sulfur and nitroxyl (heteroatoms) emit later during post pulsed-flame conditions. This delay allows their flame emissions to be electronically "gated." By using gated signal-processing methods that record data in separate time windows (or channels) of a few milliseconds, analytes can be distinguished by their heteroatoms. The PFPD offers unique heteroatom identification capability and essentially infinite selectivity over hydrocarbons.

Spectral intensity

Spectral intensity analyzers (Figure 8) measure the radiant power of emission from an analyte due to nonradiational excitation. These instruments are most often used for halide detection. Spectral intensity instruments have limits of detection in the tens of ppm range and have limited selectivity, i.e., they can differentiate halogenated compounds from nonhalogenated compounds, but cannot differentiate between halogenated compounds.

Colorimeters

A special case of visible spectroscopy is colorimetry. Colorimeters collect air samples either on a tape or in a liquid. A color change occurs between the reagents in the tape or liquid and the target chemical. The ability of this colored product to absorb light in the visible region is exploited to determine the air concentration of the target chemical. A photocell detects the color change, analyzes it and converts it to a concentration. These devices can be length of stain or color intensity where concentration is related to the degree of color change as compared to a standard. These instruments are useful for such toxic species as toluene diisocyanate, ammonia, phosgene, arsine, and hydrogen cyanide. These instruments can be quite specific through careful selection of the chemistry for the sampler, and the ability to change the chemistry makes these instruments potentially useful for a wide variety of compounds. Colorimeters have limits of detection in the low ppm range and are very specific for the contaminant(s) of interest. They are fairly complex with mechanical, optical, and electronic systems which require preventive maintenance. One type of liquid instrument is chip measurement system which contains ten capillaries filled with a substance-specific reagent (Figure 9).[10]

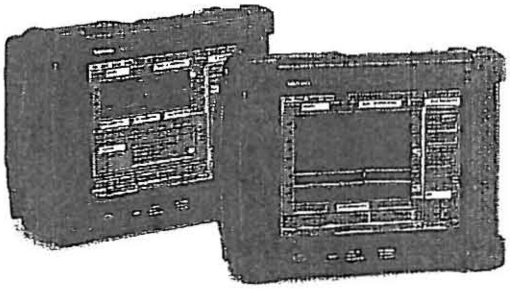

Figure 8. Spectrum analyzers.

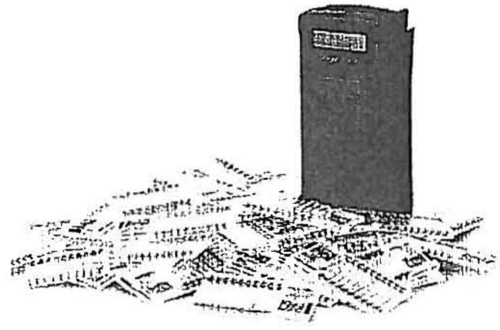

Figure 9. Dräger chip-measurement-system for spot concentrations.
Photograph courtesy of Draeger Safety Inc.

AEROSOL METHODS

Colorimetric Methods

Colorimetric tubes can be used to measure the concentration of certain aerosols (i.e., arsenic trioxide, cyanides, chromic acid, nickel, oil mist and sulfuric acid). These tubes employ a two-stage procedure. In the first stage, the aerosol is collected on a suitable medium such as a filter contained in the tube. After collection, the aerosol is brought into contact with the reagent system contained in an ampoule inside the tube. The ampoule is broken, releasing the reagent and a color reaction takes place.[11] Colorimetric tubes for aerosols have the same advantages and disadvantages as those for gases and vapors.

Optical Particle Monitors

Photometers

Light-scattering aerosol monitors (also called nephelometers or aerosol photometers) operate by illuminating aerosol passing through a defined volume and detecting the total light scattered by all the particles in that volume (Figures 10 and 11). The light source of a photometer can be monochromatic such as a light-emitting diode or laser or a broad-wavelength light source such as a tungsten filament lamp. The choice of light source in different instruments has more to do with the ability to control the light output level than with the wavelength of the output. The detector is generally a solid state photodiode but can be a photomultiplier tube. The detection geometry varies from one instrument to another. These instruments generally use a forward-scattering geometry (i.e., less than 90°). The angle of scattering (theta) is defined with respect to the beam of light passing through the aerosol in the detection volume. The smaller the value of theta the more the detection is weighted toward larger particles. The amount of light scattered by a particle into the detector is a complex function of the particle size, shape and refractive index. For spherical particles of known refractive index the instrument response can be calculated. However, in general, calibration must be carried out experimentally. For quantitative measurements, it is necessary to calibrate with an aerosol similar in refractive index and particle size to the one being measured. This is because aerosols with different refractive indices can produce photometer responses differing by more than a factor of 10. Since these instruments have specific size-dependent response to particles, the size distribution of dust particles is also important in evaluating the mass response of the instrument for a specific dust. Photometers can be affected by high humidity since they detect water droplets. Due to some aerosol properties, there may

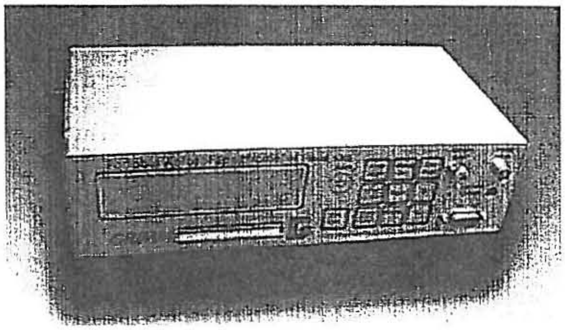

Figure 10. 31 Channel real-time aerosol spectrometer.
Photograph courtesy of GRIMM Technologies, Inc.

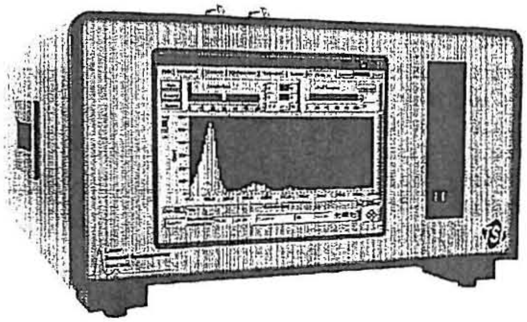

Figure 11. Lasar aerosol spectrophotometer.
Photograph courtesy of TSI, Inc.

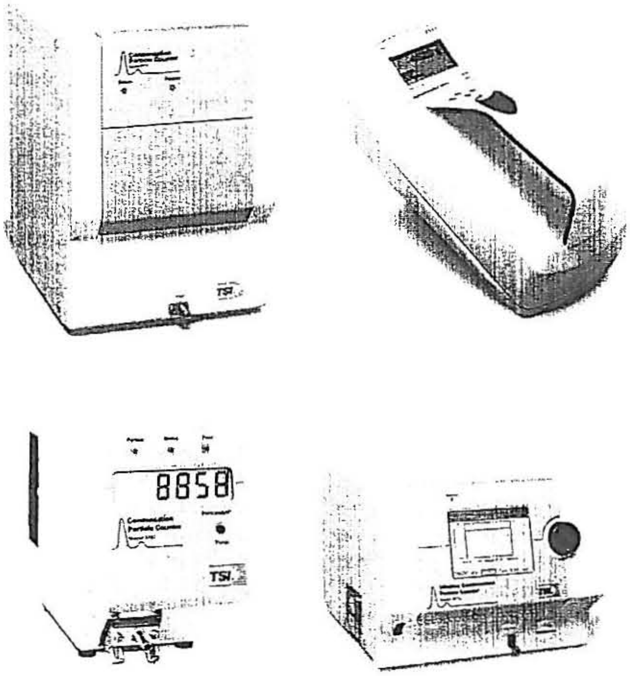

Figure 12. Different styles of condensation nuclei counters.
Photographs courtesy of TSI, Inc.

particle losses inside a photometer resulting in errors in the aerosol concentration and/or distribution. The advantages of photometers are they ability to measure aerosols continuously and they are simple to operate.[12]

Condensation particle counters

Condensation particle Counters (CPCs) are monitors that detect ultrafine particles which are too small to be detected optically (Figure 12). A CPC is based on three processes: (1) supersaturation of water or other working fluids, (2) growth of particles by condensation of vapors, and (3) detection of particles. In a CPC, the aerosol is first saturated with a vapor of water or alcohol and then cooled to induce a supersaturated condition (the vapor pressure is greater than the saturation pressure at a given temperature). The vapors then condense on the aerosols to produce larger droplets. These droplets then cross a laser beam of light optic where each droplet scatters light onto a detector. These signals are continuously counted and are expressed in particles/cm^3. If the particles were not "grown" into larger droplets, they would not produce (scatter) enough light to be detected.[13] CPCs have a maximum concentration range of approximately 5×10^5 particles/cm^3 which under certain circumstances maybe exceeded in both indoor and outdoor environments.

Wide-range aerosol spectrometer

The Wide-range Aerosol Spectrometer (WARS^{TM}) measures aerosol concentration and size from 10 to 10,000 nm (0.01–10 μm) in diameter through the use of laser light scattering, differential mobility analysis, and condensation particle counting (Figure 13). This instrument can be used for atmospheric aerosol measurement, indoor-air-quality research, and the characterization of emission source particles.

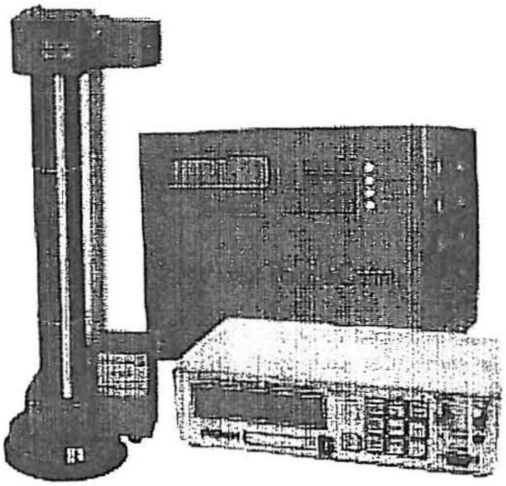

Figure 13. Wide range aerosol spectrometer.
Photograph courtesy of Grimm Technologies, Inc.

Tapered Element Oscillating Microbalance

A tapered element oscillating microbalance (TEOM) measures the aerosol mass continuously using a microbalance which consists of a hollow glass tapered tube clamped at one end while the other is free to oscillate.[14] An exchangeable polytetrafluoroethylene (Teflon) coated glass fiber filter is placed on the free end. The frequency of oscillation is measured and recorded by the microprocessor. The frequency of the oscillation of the filter changes as aerosol is deposited. This change in frequency is used to calculate the mass of the particulate matter deposited on the filter. The advantages of the TEOM include direct, NIST-

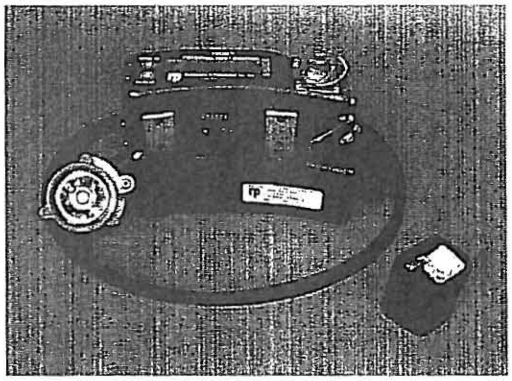

Figure 14. TEOM incorporated into a personal dust monitor for coal mine exposure assessments.
Photograph courtesy of NIOSH.

traceable mass measurement, near real-time, sub-micron sensitivity, and ruggedness. Applications for the TEOM include source identification and control, short-term compliance monitoring, and emergency response. A wearable TEOM has been developed into a person-wearable dust monitor for measuring for use in underground coal mining (Figure 14).

Time-of-flight Mass Spectrometry

Time-of-flight mass spectrometry is a method of mass spectrometry in which ions are accelerated by an electric field of known strength. This acceleration results in an ion having the same kinetic energy as any other ion that has the same charge. The velocity of the ion depends on the mass-to-charge ratio. The time that it subsequently takes for the particle to reach a detector at a known distance is measured. This time will depend on the mass-to-charge ratio of the particle (heavier particles reach lower speeds). From this time and the known experimental parameters one can find the mass-to-charge ratio of the ion. TOEMs allow for the immediate identification and classification of individual particles to guide field sampling decisions. They allow single particle detection of high molecular weight molecules such as biological aerosols and oligomers (i.e., molecules consisting of a relatively small and specifiable number (normally less than five) monomers. They are used to detect particles in the size range of 50–3000 nm.[15]

Beta Attenuation

Beta attenuation instruments contain a small carbon-14 beta source (60 μCi) coupled to a sensitive detector that counts the emitted beta particles. A filter tape is placed between the beta source and the detector. At the beginning of the sampling period, beta ray transmission is measured across a clean section of the filter tape. This section of filter tape is then mechanically advanced to the sampling inlet. Particulate matter is then drawn into the sample inlet and deposited on the filter paper. At the completion of the sampling period, the filter tape is returned to its original location and the beta ray transmission is re-measured. The difference between the two measurements is used to determine the particulate concentration. As the mass deposited on the filter tape increases, the measured beta particle count is reduced according to a known equation. Beta-attenuation mass monitors can be used for long duration, unattended remote operation. They have low operating costs. They can be used in concentrations up to 10 mg/m^3. Beta attenuation instruments conduct automatic zero and span calibrations during every cycle which helps to ensure the quality of the data.

Scanning Mobility Particle Sizer/ Differential Mobility Particle Sizer

Scanning mobility particle sizers (SMPSs) and differential mobility particle sizers (DMPSs) are similar in their operation. Both SMPSs and DMPS are based on the principal of the mobility of a charged particle in an electric field. Particles entering the system are neutralized (using a radioactive source) such that they have a Fuchs equilibrium charge distribution. They then enter a differential mobility analyzer (DMA) where the aerosol is classified according to electrical mobility, with only particles of a narrow range of mobility exiting through the output slit. This monodisperse distribution then goes to a CPC which determines the particle concentration at that size. The DMA consists of a cylinder, with a negatively charged rod at the center. The main flow through the DMA is particle free air (commonly called the sheath flow since it will surround the particles). The particle flow is injected at the outside edge of the DMA, particles with a positive charge move across the sheath flow towards the central rod, at a rate determined by their electrical mobility. Particles of a given mobility exit through the sample slit at the top of the DMA, while all other particles exit with the exhaust flow. The size of particle exiting through the slit is determined by the particles size, charge, central rod voltage, and flow within the DMA. By exponentially scanning the voltage on the central rod, a full particle size distribution is built up. These instruments are used in determining worker exposure to nanomaterials, indoor-air-quality measurements, filter efficiency testing, and characterizing sprays, powders, and other generated aerosols. SMPS/DMPS systems measure particles from 2.5 to 1000 nm. Their operating concentration range is 1–10^8 particles/cm^3. They are easy to transport and set up.

Aerodynamic Particle Sizer

Time-of-flight aerodynamic aerosol analyzers are a class of instruments that measure the aerodynamic diameter of individual particles following a controlled acceleration in a well-defined flow field. Because time-of-flight aerodynamic sizing accounts for particle shape and is unaffected by index of refraction or light scattering by the particle, it is superior to sizing by light scattering. In addition, the monotonic response curve of the time-of-flight measurement ensures high-resolution sizing over the entire particle size range. APSs are used for measuring airborne solids and nonvolatile liquids. An APS can size particles having aerodynamic diameters in the range from 0.5 to 20 μm. They can be used in concentrations ranging from 0.001 to 10000 particles/cm^3 (the maximum recommended concentration is 1000 particle/cm^3). They are useful in filter and air-cleaner testing, biological aerosol investigations, ambient air monitoring, and indoor air-quality testing.

Fiber Monitors

Real-time fiber monitors detect and count airborne fibers such as asbestos, mineral wool, advanced composites, ceramic and glass, using the principle of electric-field-induced fiber alignment and oscillation. They can be used to check and verify worker safety during asbestos remediation and removal operations and during manufacturing processes that use fibrous raw materials. They may also contain a filter from which one can obtain samples for later chemical or physical analysis, such as comparison with phase contrast microscopy. The detectable fiber length is approximately 2 to 200 μm. The detectable fiber width is 0.2 to 20 μm.

DISCUSSION

Direct-reading methods are being more widely used to examine the potential for respiratory exposure of workers. Boylstein et al. used a real-time optical particle counter during the handling of four different powder butter flavorings.[16] The monitor was used to measure the aerosol size distribution and concentration while the powders were scooped from their containers into a weighing tub in three different handling manners: (1) easy: operator gently scooping powder; (2) hurried: worker rushing while performing the task; and (3) dropped: where the powder was dropped from a height of one foot into the weighing tub to simulate an extremely hastened transfer of powder. The results of this air sampling indicated the handling of different powder flavors revealed the presence of particles of respirable size from all four powders tested, indicating the potential for inhalation of this airborne dust into the lungs. In the same study, they used an IR for diacetyl and were able to determine the level peaked at 83 ppm near the breathing zone of a mixer for approximately 5 minutes during mixing activities, which included pouring several five gallon containers of liquid butter flavoring into mixing tanks.

Choosing the proper DRM is a multifaceted process that requires knowledge of the environment to be measured and the end use of the measurements. The choice of an instrument will be based upon:

- Use of data – identify immediate hazards (flammability, explosiveness, immediately dangerous to life or health, oxygen deficiency, etc.), monitor longer-term hazards (determine compliance with occupational exposure limits), or use as a survey tool [to determine efficacy of environmental controls (ventilation) or pin point high concentration sources (either from work practices or leaks)];
- Contaminants – known or unknown;
- Chemical class (for gases and vapors) – organic vs. inorganic;
- Particle size for aerosols;
- Concentration – low vs. high; peak vs. constant level exposure;
- Instrument physical classification – personal, portable, transportable, or fixed (active vs. passive);
- Sampling strategy development – define areas to be sampled with conventional non-direct-reading methods (e.g., charcoal tubes, gravimetric, etc.).

The users of DRMs recognize that DRM results need to correlate with conventional non-direct-reading exposure assessment methods such as gravimetric sampling for aerosols or charcoal tubes for volatile organic vapors. Several studies have compared the responses of portable direct-reading photoionization detectors with charcoal tube analysis.[17–19] Drummond placed a standard charcoal tube on the outlet of a PID equipped and tested this system in both the laboratory and field measuring the exposure of a truck driver loading gasoline.[17] He found that a consistent response factor could be determined by taking the time-weighted average (TWA) concentration from the charcoal tube and dividing it by the TWA concentration of the PID.

Poirot et al. compared the response of a PID with charcoal tubes in the laboratory using six different VOCs.[18] They conducted the same type of comparison at two different workplaces – during house painting and industrial site reclamation. The workplace sampling was used to determine whether the exposures exceeded either the long-term (8-hour TWA) or short-term (15 minutes) exposure limits. Good correlation was found between the PID responses and the charcoal tube concentrations in both the laboratory and in the workplaces. They concluded the PID is an excellent means to show possible changes in a worker's exposure.

Coy et al. compared 26 side-by-side TWA personal breathing samples on construction painters using standard charcoal tubes analyzed by gas chromatography and a RAE Systems "Professional PID."[19] The data suggested the PID response was representative of the TWA total hydrocarbon exposure. The authors concluded the use of a PID was appropriate to assess exposures to solvent mixtures.

Users of DRMs also expect multiple units of the same method to provide the same responses in the same environment. Therefore, researchers are beginning to use several instruments of the same type to simultaneously measure different locations within a facility during exposure assessment studies.[20] To test this assumption, a recent NIOSH study determined the inter- and intra-direct-reading organic vapor monitor (DROVM) performance using multiple units of five different DROVMs under varying temperature, relative humidity (RH), and concentration.[21] The five different types of DROVMs used in this study did not provide accurate and precise measurements in comparison to charcoal tube samples of hexane. The DROVM variability prevented conclusive determinations about the effects of temperature, RH, and concentration on instrument performance. A high degree of variability was seen between units of the same DROVM group sampling the same atmosphere as well as between groups. Since the DROVMs were not consistent with the conventional method, charcoal tubes, they may not be suitable for compliance monitoring. Although the DROVMs' performance was poor in quantifying hexane to within 25% of the average charcoal tube concentration, their utility as survey meters to identify exposure sources or concentration profiles seems to be appropriate.

Sampling strategies for direct-reading methods especially instruments or monitors still pose a challenge and need refinement. Questions that need answering are:

- Should the same sampling strategy as for conventional methods (8-hour TW A) be used for direct-reading monitor?
- Should more sites be monitored at shorter intervals since the results can be obtained in a shorter time?
- Since some direct-reading monitors can log large amounts of data, how should the results be interpreted?
- Should a field calibration performed before each measurement or can the monitor be calibrated before going to the survey site and will the calibration still be valid?

Current regulations can both help and hinder the use of direct-reading methods. For example, the Occupational Safety and Health Administration in the Cotton Dust standard has an equivalency evaluation procedure which has been applied to other standards.[22] However, the Mine Safety and Health Administration (MSHA) coal mine dust monitoring regulations do not have such a procedure and stipulate only non-direct-reading methods for coal dust exposure assessment.[23] Since 2003, NIOSH has been working with MSHA to allow the use of the direct-reading personal dust monitor (Figure 14) in mines for compliance purposes.[24]

SUMMARY

Many instruments are available for direct-reading analysis of air containing gases and vapors and aerosols. They operate on a variety of detection principles and vary in performance characteristics such as linear range, specificity, and limits of detection. Direct-reading instruments represent a powerful tool in developing sampling strategies. When correctly used, these instruments can determine in real or near-real time areas of high concentration, workers at highest risk, and processes with the highest emissions. This information can guide the hygienist or safety professional in obtaining samples based on conventional methods and requiring laboratory analyses.

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