This monograph will be included in a future ACGIH® *Signature Publication* that will be entitled:
Air Sampling Technologies: Principles and Applications.

Direct-Reading Instruments for Gas and Vapor Detection

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INTRODUCTION

The advantages of direct-reading instruments (DRIs) are well known. Unlike conventional methods that require shipment of samples to a laboratory for analysis, DRIs allow rapid, on-site monitoring of the contaminants of interest. They permit immediate estimates of exposure hazards so that actions can be taken to quickly minimize exposure, and they are essential tools for evaluating exposure controls. This monograph presents useful information on commercially available, direct-reading instruments for measurement of airborne gases and vapors.

Direct-reading instruments may be used for area, process, or personal monitoring. The contaminants of interest are determined by nonspecific and/or chemispecific detectors and reported in relevant units (e.g., ppm, mg/m^3). It is convenient to describe four groups of DRIs: 1) personal instruments are those designed to be worn by an individual; 2) portable instruments are hand-held or easily carried using handles or shoulder straps; 3) transportable instruments are those requiring a cart or other support for movement to or from the monitoring site; and 4) fixed position instruments are those permanently installed at a specific location.

Most DRIs contain a sampling system, a detector, signal processing electronics, and a display. 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 analyte into an electrical signal. The most sensitive and popular detectors are based on electrical or thermal conductivity, electron capture, flame ionization, flame photometry, ultraviolet or infrared absorption, chemiluminescence, heat of combustion, and mass spectrometry. 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.

This monograph is divided into sections describing the operational, physical, and performance characteristics of DRIs. Each section provides a general definition of the instrumentation to be described, an explanation of the principle of detection, and a brief discussion of instrument application, including capabilities, restrictions, and limitations. A suggested reading list is provided at the end of the monograph for readers who require more in-depth information.

ELECTROCHEMICAL INSTRUMENTS

Electrochemical techniques$^{(1-3)}$ involve the measurement of electrical signals associated with chemical systems. These chemical systems are typically incorporated into electrochemical cells containing an electrolyte. Sensor operation depends on changes in signals at two electrodes inside the cell due to redox reactions of the gas or vapor at the electrodes. Electrochemical techniques include instruments that operate on the principles of conductivity, potentiometry, coulometry, and ionization.

Conductivity

Instruments that measure conductivity rely on the fact that charged species (ions) conduct electricity. Equally significant is the fact that at low analyte concentrations, such as those typically found in workplace air, conductivity is proportional to concentration. The fundamental equation for conductivity is given by

$$G = \frac{\Lambda C}{1000K} \tag{1}$$

where G = conductance in Siemens
Λ = equivalent conductance in Siemens per centimeter-equivalent
C = the concentration in equivalents per 1000 cm^3
K = a geometric term describing the electrochemical cell

A conductivity measurement depends on the separation between and area (size) of a pair of electrodes, and also on the volume of solution between them. Because conductance is the reciprocal of resistance, that is,

$$G = \frac{1}{R} \tag{2}$$

where R is resistance in ohms, the latter is sometimes measured because it is a more fundamental property. Species monitored by conductivity need not be in an ionic form in the vapor phase, but may be gases or vapors that form electrolytes by chemical reaction in solution. A special case of conductivity instrumentation is one wherein a gold film is used to amalgamate mercury (Hg). In the mercury conductivity detector, the change in resistance of the solid film is measured.

Conductivity measurements are temperature dependent, having a temperature coefficient that can be on the order of 2% per °C. Some instruments have detectors housed in thermostatted cabinets to maintain constant temperature, while others compensate for temperature effects electronically.

Conductivity is typically a nonspecific technique in that any species that is ionizable under the given conditions will affect the measurement. The specific conductance (λ) of each ionizable species is important, because only when the conductivity of interfering electrolytes is either constant and/or negligible can the conductivity of the species of interest be measured.

There also are several solid-state devices that exploit electronic conductivity charges induced in metal oxide semiconductors.(4) Their principle of operation is based on the change in surface conductivity of a semiconductor, such as SnO_2, as a result of gas adsorption. The adsorbed gas may either directly affect the conductivity, or interact with the surface oxygen coverage, which in turn affects the conductivity. These instruments are relatively inexpensive, easy to use, and can be operated in oxygen-depleted atmospheres. They are typically used in screening applications and for hazard warning.

Conductivity instruments are primarily used for detection of corrosive gases, e.g., ammonia (NH_3), hydrogen sulfide (H_2S), and sulfur dioxide (SO_2). They are most effectively used in isothermal environments at or near room temperature and with little interference. Chemical prescrubbers may be required to remove interfering compounds.

Potentiometry

Instruments that rely on a change in electrochemical potential as their principle of detection are most commonly represented by the pH meter. Potentiometry is strictly 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, thereby effecting oxidation/reduction, the extent of which is proportional to the concentration of the reacting gas. The fundamental equation governing a potentiometric reaction is the Nernst equation:

$$E_{cell} = E^o_{cell} - \frac{RT}{nF} \ln \frac{[C]^c[D]^d}{[A]^a[B]^b} \tag{3}$$

where E_{cell} = cell potential
E^o_{cell} = standard cell potential
R = gas constant
T = temperature
n = number of electrons involved in the electrode reaction
F = Faraday constant

Although the letters in brackets strictly represent the chemical activities of the reacting species, when considering dilute solutions, it is reasonable to approximate the activity using the concentration. This equation is simplified at nominal room temperature (25 °C) by converting to the base 10 logarithm and substituting for the constants: R = 8.314 Joules mol^{-1} T^{-1}, T = 298 K, F = 96,485 Coulombs/mol. This results in the following equation:

$$E_{cell} = E^o_{cell} - \frac{0.591}{n} \log \frac{[C]^c[D]^d}{[A]^a[B]^b} \tag{4}$$

The Nernst equation relates the measured potential, E_{cell}, with temperature, the electronic state change of the species being oxidized or reduced, and the concentration of the species. When sampling with a potentiometer-based device, the analyte of interest would most likely be represented by one of the reactants, A or B.

Potentiometry is basically a nonspecific technique, but some degree of specificity can 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, oxides of sulfur, oxygen, and ozone. These instruments typically perform best at or near room temperature.

Coulometry

Coulometric analyzers determine the quantity of electricity (current) required to complete the 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. In both cases, the equation governing coulometry is Faraday's:

$$W = \frac{qM}{nF} \tag{5}$$

where W = mass of substance that is electrolyzed
q = charge, in Coulombs, required to completely electrolyze the substance
M = molecular (or atomic) weight (g/mole)
n = moles of electrons per mole analyte (molecule or atom) required for electrolysis
F = Faraday's constant: 96,485 Coulombs/mole

The quantity that a coulometric instrument must measure is q. This may be done either directly, by determining the integral of the passed current (controlled-potential coulometry), or indirectly, by measuring the time required for electrolysis under conditions of constant current (constant-current coulometry). Both approaches are based on the following relationship:

$$q = \int i \, dt \tag{6}$$

where i = current in amperes
t = time

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 coulometric analyzers are also available for carbon monoxide, chlorine, hydrogen cyanide, hydrogen sulfide, oxides of nitrogen, ozone, and sulfur dioxide. Coulometric detectors can be personal or area monitors, and pumped or passive samplers.

IONIZATION

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

Flame Ionization

The FID responds to ions generated when a gaseous sample is burned in a hydrogen/air flame.[5] The internal arrangement of a typical flame ionization detector is shown in Figure 1. A gaseous sample (e.g., effluent from a gas chromatograph [GC]) enters at the detector base and is mixed with the hydrogen combustion gas (plus optional makeup gas) in the area below the flame jet. This mixture is then combined with air and burned just above the jet tip. The process produces positively charged ions and electrons that are carried through the flame to an electrode gap, decreasing the gap resistance. A negative polarizing voltage is applied between the jet tip and a collector electrode. As electrons are formed, they are accelerated across the jet tip-collector gap by the electric field and sent to an electrometer. Air, carbon dioxide, and water exhaust gases are vented from the top of the detector body.

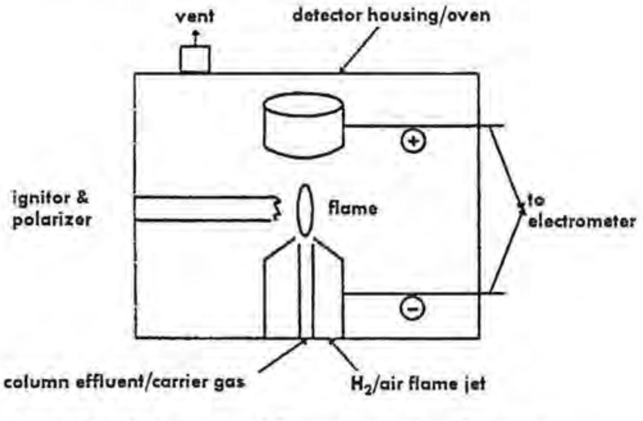


FIGURE 1. Schematic of Flame Ionization Detector

Reactions in flame ionization include:

$$CH_3COCH_3 \rightarrow CH_3 + CH_3CO$$
$$H + C_3H_8 \rightarrow C_3H_7 + H_2$$

There can be matrix reactions that give energetic intermediates exemplified by:

$$H + 3\,HO_2 \rightarrow 4\,OH^* + O_2$$

and it is possible to ionize one species using excited components from the matrix as in:

$$CH_2 + OH^* \rightarrow CH_2OH^+ + e^-$$

The FID has a wide linear range, on the order of 10^6 to 10^7. It is a very sensitive detector for organic compounds and is excellent in trace analysis. A typical measurement range is from 100 ppb to several percent.

Flame ionization is a nonspecific detection method for most organic compounds, but the response is best for hydrocarbons. Molecules that contain "heteroatoms" such as oxygen reduce the detector's response. For example, the FID's response for methane (CH_4) is excellent, but its signal for formaldehyde (CH_2O) is poor. The detector 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 (H_2O, CO, CO_2, SO_2, NOx). 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. Because their operation requires a flame, they should not be used in combustible/flammable atmospheres.

Photoionization

Photoionization is a flameless ionization technique wherein the contaminant gas or vapor is ionized in an ionization chamber containing an ultraviolet (UV) lamp of a known, constant voltage. Molecules having ionization potentials less than the energy emitted by the lamp are ionized.[6] That is, photoionization occurs when a molecule absorbs a photon of sufficient energy to cause the molecule to lose an electron and become a positively charged ion:

$$RH + h\nu \rightarrow RH^+ + e^- \qquad (7)$$

where RH = molecule to be ionized
$h\nu$ = energy of a photon, where h is Planck's constant and ν is the photon's frequency

(For photoionization to occur, the photon energy must be greater than the ionization potential of RH.)

RH^+ = ionized molecule

e^- = electron lost in the process

The PID has a high-voltage, positive bias electrode to repel the positively charged molecules, thereby accelerating the ions toward a negatively charged collector electrode. This, in turn, generates a signal (current) at the collector which is proportional to the amount of ionized species.

The classical PID contains a glass discharge UV lamp constructed of a sealed glass volume containing inert gas (helium, argon, krypton, or xenon) and a window made of a UV transparent material (e.g., magnesium fluoride, lithium fluoride, barium fluoride, strontium fluoride, calcium fluoride or sapphire). The lamp also contains two electrodes. A voltage applied across the electrodes excites the gas inside, and photons are emitted as the excited gas returns to the ground state.

An alternative PID design is shown in Figure 2. This design eliminates the need for electrodes in the glass volume. Instead, gas in the glass volume is excited by an inductively coupled radio frequency (rf) source that produces UV radiation uniformly across the cross-section of the lamp. The glass volume is supported in a holder made of polytetrafluoroethylene, around which a coupling inductor is wound and connected at one end to the rf source.

A PID can be somewhat selective through judicious choice of UV lamps of varying energies. Most PIDs have only one lamp, but lamps can be exchanged depending on the compound selectivity sought. The available lamp energies range from 8.3 to 11.7 electron volts (eV) (λ = 149 to 106 nm). Typical lamp energies are 10.6 or 11.7 eV, with 10.6 eV being the most common. A 10.6 eV lamp can ionize compounds with ionization potentials below 10.6 eV, such as benzene, toluene, ethylbenzene, xylenes (BTEX) and hexane. Chlorinated compounds with double bonds, such as trichloroethylene and tetrachloroethylene, have lower ionization potentials and can be detected by lower energy lamps, while chlorinated compounds with single bonds, such as methylene chloride and 1,1,1-trichloroethane, require higher energy lamps for ionization.

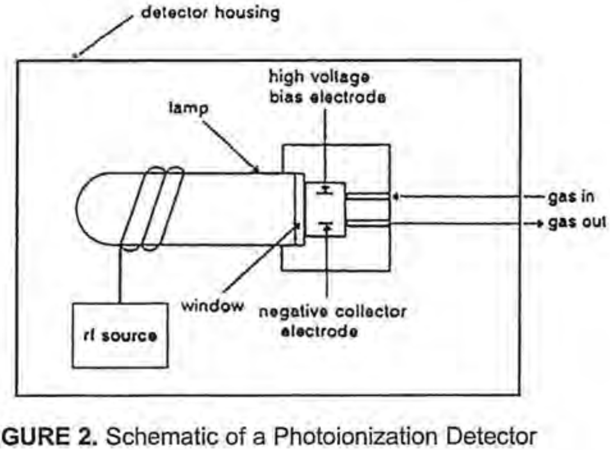


FIGURE 2. Schematic of a Photoionization Detector

Compounds routinely analyzed by PIDs include aromatic hydrocarbons, or heteroatoms containing compounds such as organosulfur or organophosphorus species, as these compounds have ionization potentials within reach of commercially available UV lamps. PIDs are useful for detection of some permanent gases such as methane and ethane, but most light permanent gases (hydrogen, helium, nitrogen) have ionization energies higher than 10.6 eV and do not give a response. When using higher energy lamps, the possible interference of water vapor or oxygen must be considered.

PIDs have traditionally been area/survey instruments, but personal PIDs have become available. While primarily used for the detection of organic compounds, the PID has some utility for inorganic compounds such as nitric and sulfuric acids, hydrogen sulfide, arsine, and phosphine. The PID has a typical linear dynamic range from about 0.1 ppm to 10,000 ppm. The limit of detection for most contaminants is about 0.1 ppm. Under optimum conditions, PIDs can detect 5 pg of benzene.

Electron Capture

The ECD uses a radioactive beta particle (electron) emitter, usually nickel-63 (^{63}Ni). The original ECD source was tritium absorbed into silver foil, but this source was thermally unstable and was soon replaced by the thermally stable ^{63}Ni. A typical source contains a metal foil holding 10 millicuries of ^{63}Ni.

Figure 3 shows a schematic of an ECD. In an ECD, electrons from an emitter collide with carrier gas molecules, causing ionization of the carrier gas (nitrogen or 5% methane/95% argon) molecules and produce a stable electron cloud.(5) In the absence of organic species, the emitted electrons are attracted to a positively charged anode, generating a constant standing current. When electronegative compounds (especially chlorinated, fluorinated or brominated molecules such as carbon tetrachloride, bromoform, polychlorinated biphenyls, and pesticides, for example DDT) in the sample stream enter the detector, they immediately combine with (i.e., 'capture') some of the free electrons to form negative ions, thereby markedly reducing the standing current. Electron capture can occur by the following two mechanisms:

$$\begin{aligned} AB + e^- &\rightarrow (AB)^- + energy \\ AB + e^- &\rightarrow A^- + B \pm energy \end{aligned} \qquad (8)$$

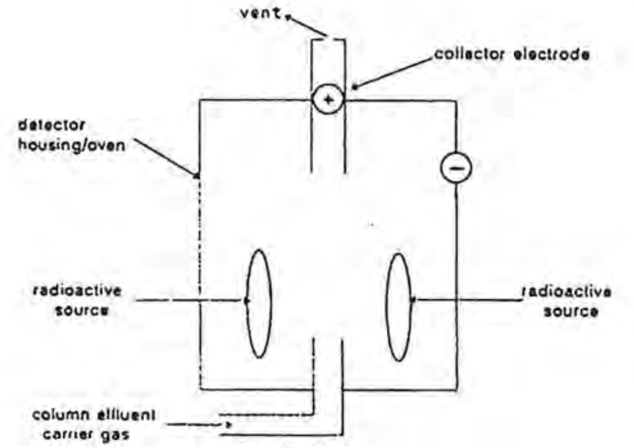


FIGURE 3. Schematic of an ECD

where A and B are reactants. The magnitude of current reduction measured is a function of both the amount of sample present and its electron affinity. The ECD response is nonlinear unless the potential across the detector is pulsed, and calibration must be made separately for each sample component that is to be quantified.

The ECD is very selective in its response, particularly for halogenated compounds (e.g., pesticides, peroxides, compounds with nitro groups, conjugated carbonyls, and some organometallic compounds); it also is useful for detection of SF_6. It is not sensitive to amines, alcohols, and hydrocarbons. An ECD is highly sensitive (as low as 0.1 pg) for the compounds it will detect (10–1000 times more sensitive than an FID, and a million times more sensitive than a thermoconductivity detector [TCD]), but it has a limited dynamic range of about 10^2–10^3. The typical measurement range is from about 1 ppb to 10 ppm.

SPECTROCHEMICAL INSTRUMENTS

Spectrochemical instruments(7-11) include infrared (IR) analyzers, ultraviolet and visible (UV/VIS) light photometers, chemiluminescent detectors, and photometric analyzers. Photometric analyzers include fluorescence and spectral intensity detectors. In general, spectrochemical analysis involves the use of a spectrum or portion 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 with matter.(7,8) Specifically, that portion of the spectrum ranging in wavelength from 770 nm to 1000 μm, or 12,900 to 10 wavenumbers. In analytical practice, frequency rather than wavelength is normally used in the infrared region. Frequency is expressed in terms of wavenumber (cm^{-1}), which is calculated as reciprocal wavelength (i.e., wavenumber [cm^{-1}] = 10,000/wavelength in μm).

The infrared portion of the spectrum is subdivided into three regions: the near-infrared (770 nm to 2.5 μm), the mid-infrared (2.5 μm to 50 μm), and the far-infrared (50 μm to 1000 μm). The terms "near", "mid", and "far" refer to the proximity to the visible portion of the electromagnetic spectrum. Infrared radiation is not energetic enough to cause electronic transitions in molecules, but it does result in vibrational and rotational transitions. 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 IR frequency for measurement of analytes in an uncharacterized mixture is unreliable because of potential interference by compounds with similar absorption frequencies.

Infrared spectrometry may be either a nondispersive or a dispersive technique. These instruments consist primarily of six major sections: a source of infrared radiation, a wavelength selector, a sample cell, appropriate optics, a detector, and a signal processor/readout. A nondispersive analyzer consists of a filter photometer employing interference filters designed for the determination of a specific pollutant, whereas a dispersive instrument relies on prisms or a grating monochromator (Figure 4) to separate radiation into its component wavelengths to obtain a complete spectrum for qualitative identification. Although Figure 4 shows the monochromator positioned after the sample cell, wavelength selection can occur before the sample cell, after the cell, or in both locations.

Modern IR instruments employ Fourier-transform (FT)

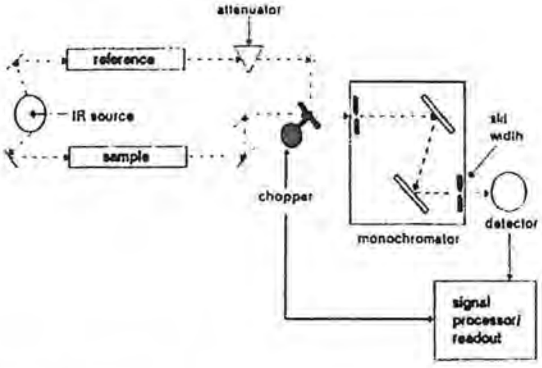


FIGURE 4. Schematic of Double Beam IR Analyzer

techniques and an interferometer to collect a spectrum.(9) An interferometer system includes an IR source, beamsplitter, two mirrors, a laser, and a detector. The beamsplitter splits the IR radiation (beam) into two parts. One part is transmitted to a moving mirror and the other is reflected to a fixed mirror. The moving mirror oscillates at a constant velocity that is timed according to the laser wavelength. The two beams are reflected from the mirrors and recombined at the beamsplitter. Because the beams from the moving and fixed mirrors travel different distances, an interference pattern, or 'interferogram', is created when the beams recombine (some wavelengths recombine constructively and some destructively). The interferogram radiation is directed through the sample, where some of the energy is absorbed and some is transmitted to the detector. The detector simultaneously processes information about every wavelength in the infrared range. To obtain the infrared spectrum, the detector signal is sent to a computer, and an algorithm called a Fourier transform is performed on the interferogram.

Because IR is an absorption technique, measuring the concentration of an absorbing species in a sample is accomplished by applying the Beer-Lambert Law (Beer's Law). Beer's Law gives the linear relationship between sample absorbance and the concentration of absorbing species. The general Beer's Law is usually written as:

$$A = \varepsilon bc \tag{9}$$

where A = measured absorbance
ε = wavelength (dependent molar absorptivity ($\mathrm{L\ mol^{-1}\ cm^{-1}}$))
b = path length (cm)
c = analyte molar concentration

Beer's Law states that the amount of light passing through the sample is attenuated by three physical phenomena: the amount of absorbing material in its path length (i.e., concentration), the distance the light travels through the sample (optical path length), and the probability that the photon of that particular wavelength will be absorbed by the material (absorptivity or extinction coefficient). Using this formula, the concentration of the component in the sample can be calculated.

The applicability of Beer's Law is limited by chemical and instrumental factors. The dependency of absorbance on path length is significant in discussing parameters of interest because the longer the path length of the instrument, the more sensitive the instrument should be. In introducing Beer's Law, it is significant to note that the absorbance (A) is log P_o/P, where P_o is the original incident radiation and P is the transmitted radiant power, or the energy remaining after some is absorbed by the sample. The linear range of IR is limited at any set path length. An additional instrument parameter of interest with dispersive instruments is the slit width. The slit width defines the window of energy seen either by the sample or by the detector. Figure 4 shows the slit width at the detector end of the instrument. The width of this slit is inversely proportional to selectivity and peak resolution.

Primarily area monitors, IR instruments balance modest precision with selectivity and high throughput. Some instruments are designed as fixed wavelength monitors whereas others are capable of scanning the infrared spectrum. Some are designed as general detectors for organics and subgroups such as hydrocarbons, while others are more specific monitors for compounds such as methane, ethylene, ethane, propane, butane, vehicle emissions, carbon monoxide, carbon dioxide, and several freons. Some IR-based combustible gas monitors, considered "active" monitors, continuously monitor the gas concentration in real time. Monitoring can be done at a single (point) location or in an open path (line of sight). Any failure in the IR source or detector, or blockage of the signal by dirt, is immediately sensed as a malfunction and triggers an alarm.

The user needs to be aware that certain ubiquitous compounds such as water and CO_2 in air absorb very strongly in the infrared. Caution must be exercised to avoid making measurements at or near these frequencies.

Ultraviolet and Visible Light Photometers

Both UV and VIS light photometers operate on the principle of absorption of electromagnetic radiation.(10) The UV is that portion of the electromagnetic spectrum that has wavelengths from about 10 nm to 350 nm. The actual spectral range for direct-reading UV instruments is closer to 180 nm to 350 nm, which is termed the "near UV", in reference to its proximity to the visible spectrum. The corresponding energy range for the UV is 3.6–7 eV for the near UV and 7–124 eV for the far (vacuum) UV. The visible spectrum (350–770 nm) has longer wavelengths than the UV and correspondingly lower energies (1.6–3.6 eV). Like their IR counterparts, the operational principle (energy absorption) of UV-VIS instruments is governed by Beer's Law, and the techniques have the same relationships between absorbance and concentration and absorbance and path length. Although the relationship between absorbance and concentration is linear, the value typically measured in spectrophotometry is transmittance. Transmittance (T) is the ratio of the amount of energy passing through the sample (not absorbed) to the amount of incident energy ($T = P/P_o$). The relationship between transmittance and absorbance (A) is given by:

$$A = \log P_o/P = \log 1/T = \log 100/\%T$$
$$A = 2 - \log \%T \tag{10}$$

Equation 10 is useful because it allows calculation of absorbance from percent transmittance data.

Figure 5 shows a schematic of a typical UV-VIS photometer. Most of these instruments are designed to analyze gaseous samples such as ammonia, mercury vapor (which absorbs very strongly at 253.7 nm), oxides of nitrogen, ozone, and sulfur dioxide.

A special case of visible spectrophotometry is colorimetry, wherein the sample is mixed with a reagent selected to react with the contaminant of interest, forming a colored product. The ability of this colored, liquid product to absorb light in the visible region is exploited. This type of instrument can be used as a continuous monitor for a variety of compounds. Primarily used as area monitors, UV-VIS instruments are capable of detecting contaminants in the ppm range.

Chemiluminescence

Chemiluminescence is a form of emission spectroscopy wherein spectral information is obtained from nonradiational activation processes.(10) In this case, the emitted energy measured results from species that are excited by chemical reactions and are returning to a lower energy state by emission of a photon. Chemiluminescence is based on the fact that, in some chemical reactions (e.g., oxidation), significant fractions of the intermediates or products are in excited electronic states. The emission of photons from these excited electronic states can then be measured, with high detection power, by a photomultiplier tube or solid state device (e.g., photo diode or charge coupled device). If the reaction conditions are carefully controlled, the quantity of emitted light in the reaction chamber is proportional to the concentration of the contaminant of interest.

The following represents a common chemiluminescence mechanism:

$$A + B \rightarrow P + P^* \tag{11a}$$

$$P^* \rightarrow h\nu + P \tag{11b}$$

where

A and B = reactants
P = product
$*$ = excited state
$h\nu$ = emitted light energy (where h is Planck's constant and ν is photon frequency)

Chemiluminescence analyzers are primarily used for measurement of oxides of nitrogen and ozone. The apparatus requires a mixing chamber wherein the target gas interacts with the reactant. The reactants are ozone for NO measurement and ethylene for ozone measurement.

The chemiluminescent reaction between ozone (O_3) and nitric oxide (NO) is a common example of the reaction mechanism(11) shown above. NO is a relatively unstable molecule that is oxidized to NO_2, especially in the presence of ozone:

$$NO + O_3 \rightarrow NO_2^* + O_2$$
$$NO_2^* \rightarrow NO_2 + h\nu$$

This reaction produces a quantity of light for each NO molecule reacted, which can be measured by a photomultiplier tube or solid state device. The chemiluminescent determination of SO proceeds by the same mechanism.

Chemiluminescence also can be applied to total oxides of nitrogen (NO_x). In this application, the sample must first pass over a heated catalyst to reduce NO_x to NO. Reduction occurs inside the instrument just prior to the ozone reaction chamber. Some instruments can automatically switch the catalyst in and out of the sample path so that the responses with and without catalyst can be compared, providing an indirect measure of NO_2.

A variation based on chemiluminescent determination of NO can be used to determine ammonia (NH_3):

$$4\,NH_3 + 5\,O_2 = 4\,NO + 6\,H_2O$$
$$4\,NO + 4\,O_3 \rightarrow 4\,NO_2 + 4\,O_2 + 4\,h\nu$$

Determination of ozone is another common chemiluminescent technique that proceeds by the following overall reaction:

$$O_3 + C_2H_4 \rightarrow O_2 + C_2H_3OH + h\nu$$

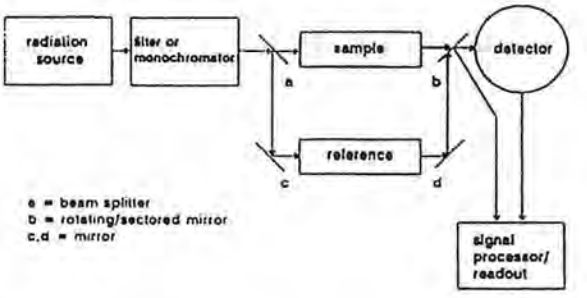


FIGURE 5. Schematic of UV-VIS Spectrophotometer

Leakage or incomplete combustion of the ethylene can be an issue with these instruments. In addition, 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.

For chemiluminescence to occur, there must be sufficient energy and a favorable reaction pathway to produce the excited state, and photon emission must be a favorable deactivation process. The chemical reactions involved give the instruments a high degree of specificity, and typical detection limits are on the order of 10 ppb.

PHOTOMETRIC ANALYZERS

This category includes fluorescence analyzers, flame photometric detectors, spectral intensity analyzers, and photometers (primarily reflectance). 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. For most molecules, electrons are paired in the lowest energy or ground state. If a molecule absorbs energy from a sufficiently powerful radiation source, such as a mercury or xenon arc lamp, the molecule will accommodate the additional energy by promoting an electron to a higher (excited) energy level. The absorbed energy is released when the electron returns to the ground state, i.e., to a lower, more stable energy condition. When returning to the ground state, the molecule can lose some of the additional energy through increased molecular vibrations of the excited state species. Fluorescence occurs when the molecule releases the remaining energy by emitting photons (light). Because some of the absorbed energy is lost through molecular vibrations, the emitted radiation (fluorescence) is usually of lower energy (longer wavelength) than the radiation used for excitation.

Figure 6 shows a block diagram of the components of a fluorescence instrument. Instrumentation used to measure fluorescence includes: 1) an excitation light source and a means to select the excitation wavelength, 2) a sample holder, 3) a means to select the fluorescence wavelength monitored, 4) a detector that generates a signal proportional to the intensity of light striking it, and 5) associated electronics and readout devices.

An excitation wavelength selector is used to limit the energy to that which will cause fluorescence of the sample, while excluding energy wavelengths that may interfere with the detection. The emission wavelength selector isolates the fluorescence peak. Detection is at right angles to allow measurement of the longer wavelength light emitted from the sample while avoiding detection of light from the source, which could cause large errors in measurement. A narrow band of excitation and emission wavelengths can make the instrument very selective and often species-specific.

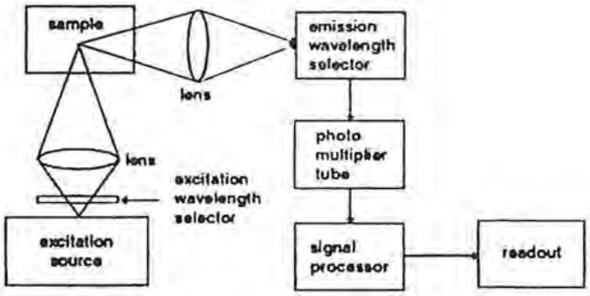


FIGURE 6. Schematic of Fluorescence Spectrometer

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, a factor that must be considered when calibrating the instrument. Fluorescence instruments are available for carbon monoxide and sulfur dioxide. Typical limits of detection are in the 5–10 ppb range.

Flame Photometry

Flame photometric detectors (FPD) can be adjusted to obtain selectivity for nanogram quantities of sulfur or phosphorous compounds. The detector operates by measuring the emission of light from a hydrogen flame. Light from the flame impinges upon a mirror and is reflected to an optical filter that allows only light with wavelengths of either 526 nm (for phosphorous) or 394 nm (for sulfur) to pass through to the photomultiplier tube. Calibration with a flame photometric detector is critical because this detector exhibits little or no linearity. FPDs have limits of detection in the low ppb range.

The pulsed FPD (PFPD) is based on a flame source and a combustible gas flow rate that cannot sustain continuous flame operation.(11) Two separate gas mixtures are fed to the detector through narrow gas lines. The primary flow, consisting of a combustible gas mixture of hydrogen and air, is supplied at the bottom of the combustion chamber (or combustor tube) along with the sample, usually from a GC column. A second combustible gas mixture flows separately into the chamber base. The function of this second flow is to fill the outer volume of the combustion chamber (tube) that is outside of the combustion zone in the center of the chamber. When the gases flowing into the chamber reach a flammable mixture, they are ignited by a heated wire igniter at the top of the chamber. The resulting flame propagates back down the chamber toward the gas source, and the flame front self terminates in a few milliseconds because it cannot propagate through a small hole at the bottom of the chamber. After the short flame pulse, slower burning analytes are excited and subsequently emit light that is characteristic of their constituent elements. The emitted light is detected with a photomultiplier tube (PMT). The continuous gas flow causes reignition after a few hundred milliseconds in a pulsed, periodic (about 3 Hz) fashion.

The PFPD is very selective because of the time domain information it provides. For example, hydrocarbon combustion is extremely fast because it is highly exothermic. Thus, hydrocarbon flame emission is limited to the time period in which the flame travels along the PMT window. In contrast, heteroatom species such as S_2, HPO, and HNO emit later during post pulsed-flame conditions. This delay allows their flame emissions to be electronically "gated". By using gated signal-processing to 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 measure the radiant power of emission from an analyte due to nonradiational excitation. These instruments are most often used for halide detection by measuring the increased spectral intensity of an AC arc (or spark) in the presence of halogenated hydrocarbons. The increased intensity can be related to the concentration of the halogenated compound by using a calibration curve based on the specific compound of interest, as each response curve for each halogenated compound will be different. 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 species.

Photometers [Other]

The remaining instruments in this category are simply referred to as photometers and have unique sampling characteristics and detection principles relative to the other instruments in this category (i.e., spectrochemical techniques). The majority of these instruments allow for unattended sampling through the use of automated sampling media advance (e.g., tape, liquid, rotating drum, rotating disc, and turntable samplers measuring reflectance) or branched sequential sampling trains. The sampling medium in these instruments typically undergoes a color change, and analyte detection is based on measurement of the light reflected from the medium. These instruments are useful for such toxic species as toluene diisocyanate, ammonia, phosgene, arsine, and hydrogen cyanide. Reflectance instruments can be quite specific through careful selection of the chemistry used for sampling, and the ability to change the chemistry makes these instruments potentially useful for a wide variety of compounds. Photometers have limits of detection in the low ppm range and are very specific for the contaminant(s) of interest.

THERMOCHEMICAL INSTRUMENTS

Gases and vapors have certain thermal properties that can be exploited in their analysis.(8) Of the instruments available for industrial hygiene applications, one of two thermal properties, conductivity or heat of combustion, is measured.

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. That is, the ability of the surrounding gas to conduct heat away from the hot body can be used as a measure of the composition of the gas. In actual practice, a TCD consists of an electrically heated element, or sensing device, whose temperature at constant electrical power depends on the thermal conductivity of the surrounding gas. The resistance of the sensing device is used as a measure of its temperature. TCDs are universal detectors, responding to all compounds. They 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). Thermal conductivity detectors require good temperature and flow control.

Heat of Combustion

A typical heat of combustion instrument is based on oxidation of a flammable gas at the surface of an electrically heated catalytic element. Combustible gases react exothermically with oxygen in air and increase the temperature of the catalytic element. The resulting temperature change, characteristic of combustible gases, can be used for their quantitative determination. Electrocatalytic detectors based on this operating principle have been in use for over 30 years and are widely used as single-point detectors for combustible gases.

The sensor in an electrocatalytic detector is normally configured as an electrical (Wheatstone) bridge, with two similar elements mounted in close proximity. The elements, also called catalytic beads or "pellistors" (from pellet and resistor), typically consist of a platinum coil embedded in a ceramic material. The sensing element also contains a surface catalyst (usually a platinum group metal) to assist combustion of the flammable gas. A heater maintains the ceramic at a temperature (400 °C to 600 °C) high enough to ensure combustion. The temperature increase caused by combustion at the surface of the sensing element induces a relative change in the resistance of the two elements that is proportional to the gas concentration.

Like TCDs, heat of combustion detectors are nonspecific universal detectors. Some specificity can be introduced by controlling the combustion temperature so that it is insufficient to burn interfering gases. In addition, some specificity can be obtained by careful selection of the oxidation catalyst.

As their name implies, heat of combustion detectors are available as generic detectors for combustible gases. Some more specific heat of combustion detectors are available for carbon monoxide, ethylene oxide, hydrogen sulfide, methane, and oxygen deficiency. Most of these instruments have displays that read out in terms of percent of the lower explosive limit (LEL) (or hundreds of ppm), and the detection limits are analyte dependent.

GAS CHROMATOGRAPHS

Gas chromatographs (GCs) are being discussed separately because there are several portable/transportable GCs commercially available that have been specifically designed for field use, they are a distinct family of instruments that address the issue of analyte separation (i.e., specificity) as well as detection in industrial hygiene monitoring, and they best represent the transfer of laboratory analytical techniques into the field. In terms of detection of airborne gases and vapors, the detectors used in GCs have, for the most part, already been discussed in this monograph.(5,6)

Figure 7 shows a schematic of a typical GC. The sample is either injected into the GC using a gas-tight syringe, or the instrument may be capable of obtaining its own sample via a built-in sampling pump. If the sample is a liquid, the instrument must be capable of vaporizing the sample (e.g., using a heated injection port).

The actual separation of the sample into its component parts takes place on the GC column.(4) Columns are typically long tubes made of metal, glass, polytetrafluoroethylene (PTFE), or fused silica. Columns in direct-reading GCs are of two kinds: packed and wall-coated. A packed column contains a granular material used as a solid support and coated with a chemical chosen for its ability to interact with the components of the sample. This chemical coating is referred to as the stationary phase. Packed columns are generally from 4 or 5 cm to 1 meter (m) or more in length and have external diameters on the order of 0.3 cm (1/8 in). Wall-coated columns tend to be longer (5 cm to 3 m or more) and narrower (i.d. from 0.1 to 1 mm) than packed columns. In a wall-coated column, there is no granular solid support for the stationary phase. It is, as the name implies, coated directly on the inner walls of the column. The long, thinner columns (i.d. < 0.5 mm) are generally referred to as capillary columns.

After sample introduction, the sample is carried through the column by an inert (relative to the sample) carrier gas which, depending on the portable GC, may be helium, hydrogen, nitrogen, argon, carbon dioxide, or air. The separation is governed by the degree of interaction of the sample with the stationary phase and the properties of the carrier gas. All components of a mixture spend the same amount of time in the carrier gas, so their different elution times are a function of the time partitioning between the stationary phase and the gas phase. The elapsed time from injection until the detector sees a component of a mixture is that component's retention time. The retention time is a function of the physical properties of a component in a sample, whereas the size of the peak (area and/or peak height) is a function of the amount. Figure 8 shows the component parts of a typical chromatogram.

The degree of separation of two components, as well as their relative retention times, depends, in part, on the temperature at which the system operates: the higher the temperature the shorter the retention time. Some portable GCs operate only at ambient temperatures, while others are

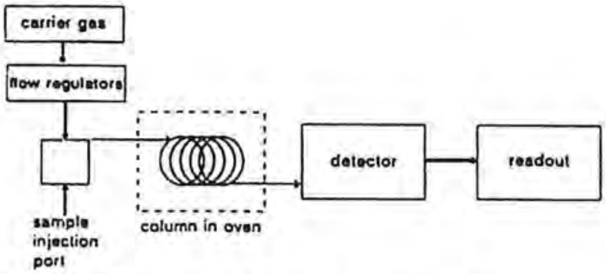


FIGURE 7. Schematic of a Gas Chromatograph

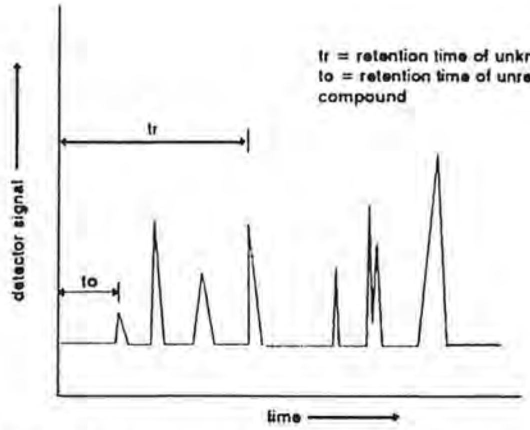


FIGURE 8. Schematic of a Typical Gas Chromatogram

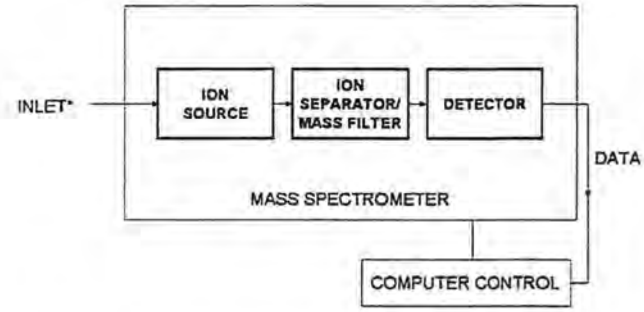
capable of column heating. As each component of a mixture elutes from the column, it enters the GC detector. Portable GC detectors include FID, PID, ECD, UV, FPD, TCD, nitrogen phosphorous (NPD), and mass spectrometers (MS). The most frequently used detectors for industrial hygiene applications are the FID and the PID.

The separation capabilities of GC confer excellent selectivity to this technique. Limits of detection are primarily a property of the individual detectors (see detector discussions), but portable GCs generally have limits of detection at sub ppm levels. Selectivity, fast results, and low detection limits are especially crucial in the field when rapid assessment of potential health hazards is necessary (e.g., hazmat incidents). Potential sample degradation during transport is avoided and sampling efficiency is improved, thereby lowering costs, and contamination boundaries can be efficiently assessed.

Limitations associated with portable GCs have included instrument size, gas requirements, initial equipment costs, and the need for more user knowledge of the technique. However, design innovations have greatly improved the utility of GC devices in the field. Self-contained, battery powered GCs with intuitive user interfaces, proprietary detectors and valve technology are commercially available. These instruments have improved peak resolution and analysis speed relative to previous models and have been designed for accurate, rapid, on-site screening of common volatile organic compounds (VOCs).

ION MOBILITY SPECTROMETRY

The Ion Mobility Spectrometer (IMS) is based on the drift of ions at ambient pressure under the influence of an electric field. The IMS is capable of detecting and identifying very low concentrations of chemicals based on the differential migration of gas phase ions through a homogeneous electric field. Certain compounds can be ionized in air (for example, using a beta-radiation source such as ^{63}Ni) to produce characteristic ionic species. The ions pass into a "drift tube" (typically a few centimeters long), where they migrate in air under a potential gradient ranging from a few to several hundred volts per centimeter (V/cm). The ions are detected at the end of the drift tube by an electrometer (Faraday plate). Species are separated according to their drift velocities or mobility, which is dependent on their mass, size, shape, and charge. Ions impinging on the detector generate a time-dependent signal that is characteristic of each substance. Separations can typically be done in tens of milliseconds. Rapid response, ease of use, relatively high sensitivity, and compact design have made the IMS a tool of choice for routine field detection of explosives, drugs, and chemical weapons. Detection limits are in the low ppb to ppt range.



*MAY BE GAS CHROMATOGRAPH INTERFACE

FIGURE 9. Schematic of a Mass Spectrometer

MASS SPECTROMETERS

Components of a typical mass spectrometer are shown schematically in Figure 9.

A mass spectrometer (MS) determines the masses of individual molecules and molecular fragments that have been ionized by an ion source in the MS, typically a 70-eV electron beam. Loss of an electron from the analyte during ionization generates a charged molecular ion with the same molecular weight as the analyte. Excess energy of the beam causes fragmentation of the molecular ion into daughter ions with lower mass-to-charge ratios. The positive molecular and fragment ions produced are attracted through the slits of the ion source and into the mass analyzer, where they are differentiated by their mass-to-charge ratios. The mass-sorted ions are detected by a transducer, usually an electron multiplier, that converts the ion flux into an electrical signal that is proportional to the flux.(12) The spectral data are processed, stored, and presented graphically. The resulting fragmentation pattern for an analyte generally produces a mass spectrum representing the chemical structure of the analyte. Analytes are ordinarily identified by comparing the spectrum to one stored electronically in a reference library.

Portable/transportable GC/MS instruments can provide real-time quantification and speciation of unknowns in the field. Separation by GC and analysis by MS allows definitive identification of a wide range of unknown components in a mixture. Other types of GC detectors identify compounds based on the retention times of analytes in the standard solutions used for instrument calibration. Therefore, with other detectors, the user must predetermine which compounds are present at the site and employ standards containing those compounds.

Mass spectrometers are currently used only for area sampling because of their size, complexity, and power requirements. Additional requisite equipment may include a gas cylinder, marine battery, or generator. Power requirements differ—some instruments operate on batteries or line current, while others use line current only. Some instruments can use ambient air as a carrier gas. Operators must determine the column temperature required for analyte separation in order to select the appropriate carrier gas.

Instruments with higher GC temperature capabilities permit shorter analysis times and determination of less volatile compounds, though the primary field application of MS is for VOC analysis. Some instruments allow direct injection into the MS, which is useful for rapid analysis of volatile components in samples that are not complex mixtures. The user must ensure that the analytes of interest are not affected by the method of sample introduction, which in turn can affect detection limits. Typically, an MS can detect compounds in air at the low ppb range.

SELECTION CRITERIA

Choosing the proper instrument is a multifaceted process that requires knowledge of the environment to be measured and the end use of the measurement results.[13] The choice of an instrument will be based upon:

- Use of data – identification of immediate hazards (flammability, explosiveness, immediately dangerous to life or health, oxygen deficiency, etc.), monitoring longer-term hazards (determine compliance with occupational exposure limits), or use as a survey tool [to determine efficacy of environmental controls (ventilation) or pinpoint high concentration sources (either from work practices or leaks)];
- Contaminants – known or unknown;
- Chemical class – organic vs. inorganic;
- Concentration – percentage levels, ppm or ppb; peak vs. constant level exposure;
- Instrument physical classification – personal, portable, transportable, or fixed;
- Sampling strategy development – define areas to be sampled with conventional non-direct-reading methods (e.g., charcoal tubes, etc.) and number of samples to take.

Tables 1 through 4 provide examples of and details on currently available instruments. The tables are organized based upon the likely use of the instruments. Table 1 lists instruments that may be used for confined space monitoring. These instruments have been classified based upon their ability to measure, at a minimum, oxygen deficiency and lower explosive limit (LEL). Table 2 lists indoor environmental quality monitors. These monitors have been configured to monitor carbon dioxide in the range typically found indoors (generally around 1,000 ppm). These monitors may also measure comfort parameters (relative humidity and temperature) and carbon monoxide. Table 3 lists single gas monitors containing only one sensor for a specific gas of interest. These instruments are not configurable by the user for monitoring other gases and vapors. Table 4 provides a listing of multigas monitors. These devices vary in their capabilities, with some being specific for particular gases or vapors and some being non-specific, providing readings for a particular class of compounds (e.g., natural gas, hydrocarbons, halocarbons, combustible gases, etc.). Some models may have user-replaceable specific gas sensors to allow monitoring of other gases.

Figure 10 provides a logic model for selecting gas and vapor monitors. The logic model has been linked to the monitor list tables to aid in the selection of a specific monitor. General summary information on the DRI detectors and other equipment described in this monograph is provided in Table 5, and contact information for instrument suppliers is provided in Table 6.

SUMMARY

Many commercial instruments are available for direct-reading analysis of gases and vapors. 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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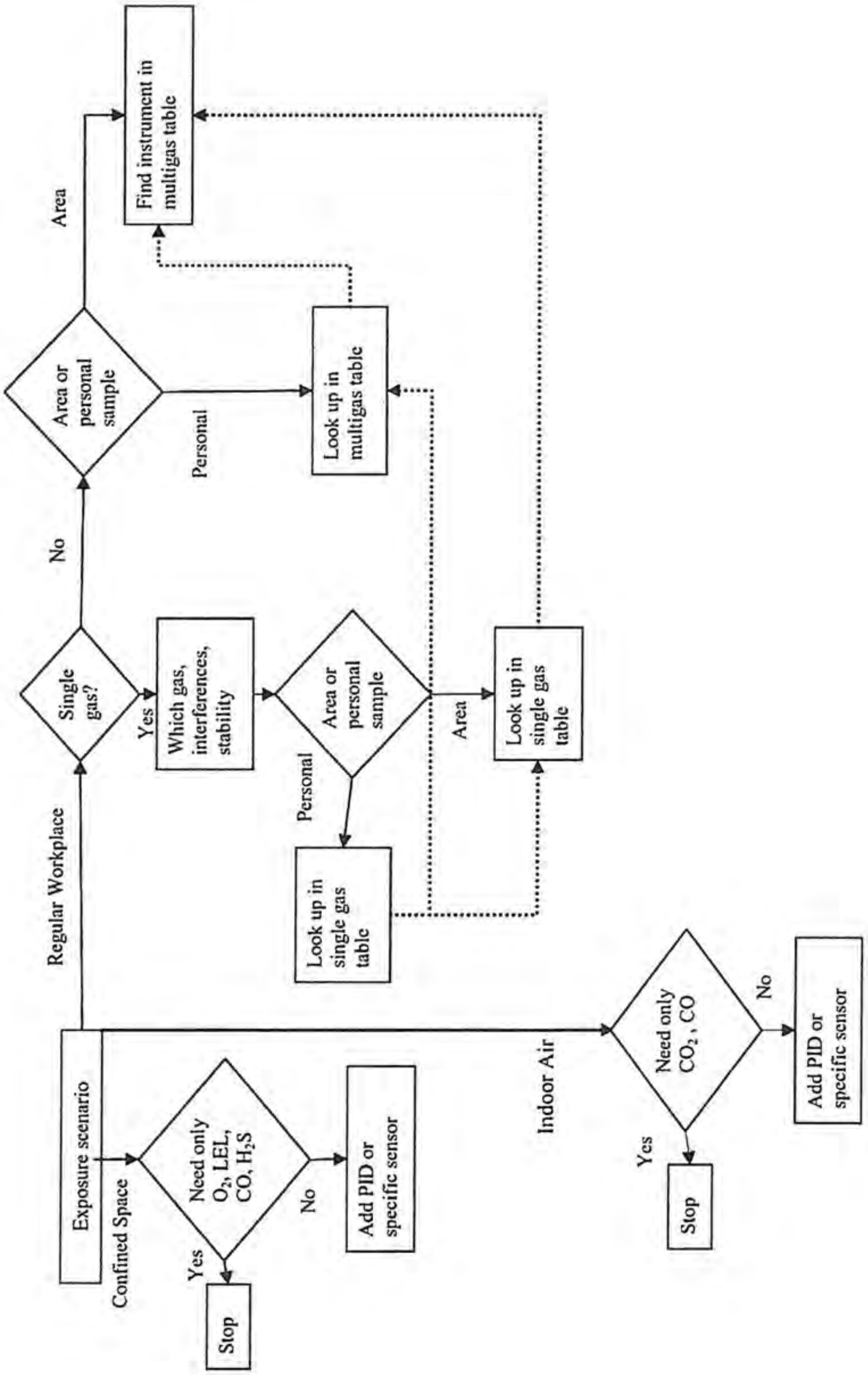

FIGURE 10. Direct-reading instrument selection flowchart

TABLE 1. Confined Space Monitors for Oxygen Deficiency and Lower Explosive Limit (LEL)

Source	Model	Configuration	Max. Number of Sensors	Additional Analytes	Power	Comments
BIO	Cannonball 3	R	4	Yes	DC	Sensors: Galvanic, Catalytic, and Electrochemical
BIO	Multipro	P	4	No	DC	Sensors: Galvanic, Catalytic, and Electrochemical
BIO	Multivision	P	4	No	DC	Sensors: Electrochemical for CO and H_2S
BIO	PhD 5	P	4	Yes	DC	Sensors: Electrochemical
BIO	PhD Lite	P	3	No	DC	Sensors: Electrochemical
BIO	PhD Ultra	R	4	Yes	DC	Sensors: Electrochemical
BWT	GasAlert Max	P	4	No	DC	Sensors: Catalytic bead and Electrochemical
BWT	GasAlert MaxXT	P	4	No	DC	Sensors: Catalytic bead and Electrochemical
BWT	GasAlertMicro	P	4	Yes	DC	Sensors: Catalytic bead and Electrochemical
BWT	GasAlertMicro 5	P	5	Yes	DC	Sensors: Catalytic bead and Electrochemical
BWT	GasAlertMicro 5 PID	P	5	Yes	DC	Electrochemical, PID Detector for VOCs
BWT	GasAlertMicroClip	P	4	No	DC	Sensors: Electrochemical
CDI	Tetra	P	4	Yes	DC	Hand aspirator
CDI	Tetra3	P	4	No	DC	
CDI	Triple Plus+	R	4	Yes	DC	Configurable with PID or IR
CSE	Explorer 4	P	4	Yes	DC	Sensors: Electrochemical
DRA	MiniWarn	R	4	Yes	DC	Sensors: Electrochemical
DRA	Pac Ex 2	P	2	No	DC	LEL and O_2 sensors only
DRA	X-am 1100/1700/2000/3000	P	4	No	DC	Sensors: Catalytic, Electrochemical
DRA	X-am 5000/7000	R	5	Yes	DC	Sensors: Catalytic, Electrochemical
ENM	Omni-4000	R	4	Yes	DC	Sensors: Metallic oxide, Catalytic combustion
ENM	Quadrant	R	4	Yes	DC	Catalytic, Electrochemical and/or O_2
ENM	Target	R	5	Yes	DC	Sensors: Metallic oxide, Electrochemical, Catalytic combustion
GFG	AGM500	R	4	Yes	DC	Hand aspirator; Sensors: Electrochemical, Catalytic combustion
GFG	CGM II 900 Autocal Series	R	5	Yes	DC	Sensors: Metallic oxide sensor, Electrochemical, Catalytic combustion
GFG	G450	R	4	No	DC	Sensors: Catalytic combustion, Electrochemical
GFG	G460	R	4	Yes	DC	CO_2 – IR and PID

TABLE 1. Confined Space Monitors for Oxygen Deficiency and Lower Explosive Limit (LEL) (Cont.)

Source	Model	Configuration	Max. Number of Sensors	Additional Analytes	Power	Comments
GFG	G750	R	6	Yes	DC	Sensors: IR, Electrochemical, Catalytic combustion, Thermal conductivity
GFG	G850	R	3	Yes	DC	Sensors: Metallic oxide, Electrochemical, Catalytic combustion, Thermal conductivity
GFG	Microtector G333	R	4	No	DC	Sensors: Electrochemical, Catalytic combustion
HON	Lumidor Impact/Impact Pro	P	4	Yes	DC	Optional pump
HON	Lumidor MicroMax Plus	P	4	Yes	DC	
HON	Lumidor MicroMax Pro	R	5	Yes	DC	
HON	Lumidor MiniMaxX4	P	4	No	DC	
ISC	BM25 Multiguard	TransR	5	Yes	DC	Sensors: Catalytic diffusion, Electrochemical, IR
ISC	iTX	R	6	Yes	DC	Sensors: Catalytic diffusion, Electrochemical
ISC	M40	P	4	No	DC	
ISC	M40-m	P	4	No	DC	
ISC	MX6	P	5	Yes	DC	Sensors: Catalytic diffusion, IR, PID, Electrochemical
MSA	ALTAIR 4	P	4	No	DC	
MSA	Orion	R	4	No	DC	
MSA	Orion plus	P	5	Yes	DC	Sensors: Electrochemical, Catalytic combustion, IR
MSA	Sirius	R	5	Yes	DC	Sensors: PID, Electrochemical
MSA	Solaris	P	4	Yes	DC	
MSA	Solaris Fire	P	4	No	DC	
MSA	WATCHMAN	R	4	Yes	DC	Combustible Sensor: Catalytic filament
RAE	QRAE	P	4	No	DC	Sensors: Catalytic bead, Electrochemical, Nondispersive IR
RAE	QRAE Plus	P	4	No	DC	Sensors: Catalytic bead, Electrochemical, Nondispersive IR
RAE	EntryRAE	R	5	Yes	DC	PID for VOCs
RAE	SentryRAE Steel	R	5	Yes	DC	PID for VOCs
RKI	GX-2001	P	4	No	DC	Catalytic, Electrochemical, Galvanic cell
RKI	GX-2003	R	5	Yes	DC	Catalytic, Electrochemical, Galvanic cell, Thermal conductivity
RKI	GX-86A	R	4	No	DC	Catalytic, Electrochemical, Galvanic cell
RKI	GX-94	P	4	No	DC	Catalytic, Electrochemical, Galvanic cell
SEN	PhoCheck Plus	R	5	Yes	DC	PID Detector for VOCs

Configuration: P = Personal, R = Portable

TABLE 2. Indoor Air Quality Monitors for CO_2

Manufacturer	Model	Configuration	Maximum Number Sensors	Additional Analytes	Power
QST	AQ5000Pro/AQ5001Pro	Portable	2	Yes	DC
TSI	Qtrak 7565	Portable	2	Yes	DC
GRA	IAQSurveyor	Portable	2	Yes	DC
TES	435	Portable	2	Yes	DC
TSI	IAQ-Calc 7515, 7525, 7535, 7545	Portable	2	Yes	DC
KDE	Airboxx	Portable	2	Yes	DC
HON	Vulcain	Portable	2	Yes	DC
BAC	Comfort Check 100	Portable	1	Yes	DC
BAC	Comfort Check 200	Portable	2	Yes	DC
QST	AQ5000Pro and AQ5001Pro IAQ Monitors	Portable	3	Yes	DC
BAC	2825/2830	Portable	2	Yes	DC
BAC	2836	Portable	1	No	DC
TES	535	Portable	1	No	DC
RAE	043-12C1-102 AreaRAE	Portable	3	Yes	DC
FLK	975 Air Meter	Portable	2	Yes	DC
KAN	2211	Portable	2	Yes	DC

TABLE 3. Single Gas Monitors

Manufacturer	Model	Configuration	Gas	Power	Sensor
ESC	IR-10M/IR-10MDL	R	Acetone	DC	IR
INT	4000/LD/RM Series	R/F	Br_2	AC/DC	Electrochemical
BIO	Toxivision *IR* CH4	P	CH_4	DC	IR
BAC	Gas Pup®	R	CH_4	DC	Catalytic Bead
CDI	LaserMethane	R	CH_4	DC	Laser Photometer
INT	4000/LD/RM Series	R/F	C_2H_4	AC/DC	Electrochemical
ESC	Z-200/Z-200XP	R	$C_5H_8O_2$	DC	Electrochemical
ESC	Z-400/Z-400XP	R	Cl_2	DC	Electrochemical
INT	4000/LD/RM Series	R/F	Cl_2	AC/DC	Electrochemical
INT	4000/LD/RM Series	R/F	ClO_2	AC/DC	Electrochemical
ESC	Z-500/Z-500XP	R	CO	DC	Electrochemical
ISC	GasBadge Plus	P	CO	DC	Electrochemical
RKI	CO-01	P	CO	DC	Electrochemical
BAC	MGC200	R	CO	DC	IR/Electrochemical
BAC	MONOXOR II/III	R	CO	DC	Not specified
BAC	Snifit 40/50	P	CO	DC	Electrochemical
CEA	Spygas CO	R	CO	DC	Electrochemical
DRA	MicroPac Plus	P	CO	DC	Photometric
DRA	PAC 1000/3000/5000/7000	P	CO	DC	Photometric
TEL	9820/9830/9832	T	CO	AC	IR
FOR	F-8010	F	CO	AC	IR
VIC	GC-401	P	CO	DC	Electrochemical
RKI	RI-411A	R	CO_2	DC	IR
TSI	8560	R	CO_2	DC	IR
BAC	2800/2810/2815/2820/2835	R	CO_2	DC	IR
BIO	Toxivision *IR* CO2	P	CO_2	DC	IR
CEA	GD-888 Series	R	CO_2	AC/DC	Non-dispersive IR
DRA	MicroPac Plus	P	CO_2	DC	Photometric
ESC	IR-20M/IR-20MDL	R	CO_2	DC	IR
ESC	Z-100/Z-100XP	R	EtO	DC	Electrochemical
INT	4000/LD/RM Series	R/F	EtO	AC/DC	Electrochemical
INT	4000/LD/RM Series	R/F	HBr	AC/DC	Electrochemical
INT	4000/LD/RM Series	R/F	HCl	AC/DC	Electrochemical

TABLE 3. Single Gas Monitors (Cont.)

Manufacturer	Model	Configuration	Gas	Power	Sensor
ESC	Z-300/Z-300XP	R	HCHO	DC	Electrochemical
INT	4000/LD/RM Series	R/F	HCHO	AC/DC	Electrochemical
RKI	FP-30/FP-40	R	HCHO	DC	Colorimetric tablet
ENM	FORMALDEMETER htV	R	HCHO	DC	Electrochemical
DRA	MicroPac Plus	P	HCN	DC	Photometric
INT	4000/LD/RM Series	R/F	HCN	AC/DC	Electrochemical
VIC	GC-701	P	H_2S	DC	Electrochemical
AZI	Jerome 631-X	R	H_2S	DC	Electrical conductivity
AZI	Jerome 860	R	H_2S	DC	Electrochemical
DRA	MicroPac Plus	P	H_2S	DC	Photometric
DRA	PAC 1000/3000/5000/7000	P	H_2S	DC	Photometric
ESC	Z-900/Z-900XP	R	H_2S	DC	Electrochemical
ISC	GasBadge Plus	P	H_2S	DC	Electrochemical
INT	4000/LD/RM Series	R/F	H_2S	AC/DC	Electrochemical
INT	4000/LD/RM Series	R/F	H_2S	AC/DC	Electrochemical
RKI	HS-01/HS-01S	P	H_2S	DC	Electrochemical
AZI	Jerome 431-X	R	Hg	DC	Electrical conductivity
AZI	Jerome 471	R	Hg	DC	Atomic absorption
AZI	Jerome J405	R	Hg	DC	Electrical conductivity
INT	4000/LD/RM Series	R/F	Hydrazine	AC/DC	Electrochemical
ESC	Z-800/Z-800XP	R	NH_3	DC	Electrochemical
ESC	Z-700/Z-700XP	R	NO	DC	Electrochemical
INT	4000/LD/RM Series	R/F	NO	AC/DC	Electrochemical
RAI	CLD	F	NO and NO_x	AC/DC	Chemiluminescence
RAI	WCLD	F	NO and NO_x	DC	Chemiluminescence
TEL	9841A/S	T	NO_x	AC	Chemiluminescence
VIC	GC-901	P	NO_x	DC	Electrochemical
BAC	Nonoxor II	R	NO_x	DC	Not specified
VIC	GC-952	P	NO_2	DC	Electrochemical
ESC	Z-1400/Z-1400XP	R	NO_2	DC	Electrochemical
ISC	GasBadge Plus	P	NO_2	DC	Electrochemical
BAC	MGC100	R	NO_2	DC	IR
INT	4000/LD/RM Series	R/F	NO_2	AC/DC	Electrochemical

TABLE 3. Single Gas Monitors (Cont.)

Manufacturer	Model	Configuration	Gas	Power	Sensor
BAC	Trace Gas Analyzer	R	N_2O	DC	Non-dispersive IR
ESC	Z-1200/Z-1200XP	R	N_2O	DC	Electrochemical
ESD	600/630	R	O_2	DC	Coulometric
ISC	GasBadge Plus	P	O_2	DC	Electrochemical
RKI	OX-1	P	O_2	DC	Galvanic cell
RKI	OX-82	P	O_2	DC	Electrochemical
SMC	55	P	O_2	DC	O_2 concentration sensor
FOR	F-8021	F	O_2	AC	Zirconium oxide
VIC	GC-501/GC-501X/GC-502/GC-502X	P	O_2	DC	Electrochemical
BAC	Oxor II	R	O_2	DC	Not specified
DRA	MicroPac Plus	P	O_2	DC	Photometric
DRA	PAC 1000/3000/5000/7000	P	O_2	DC	Photometric
ENM	OX2000	P	O_2	DC	Electrochemical
TEL	9810	R	O_3	AC	UV photometer
TEL	9810/9811	T	O_3	AC	Ultraviolet absoprtion
SPE	UV-100	R	O_3	AC/DC	UV photometer
INT	4000/LD/RM Series	R/F	O_3	AC/DC	Electrochemical
AMK	1008	R	O_3	AC	UV photometer
DRA	MicroPac Plus	P	PH_3	DC	Photometric
INT	4000/LD/RM Series	R/F	propylene oxide	AC/DC	Electrochemical
BAC	Dioxor II	R	SO_2	DC	Not specified
TEL	9850	T	SO_2	AC	UV fluorescence
TEL	9850	R	SO_2	AC	UV fluorescence
VIC	GC-801	P	SO_2	DC	Electrochemical
ESC	Z-1300/Z-1300XP	R	SO_2	DC	Electrochemical
ISC	GasBadge Plus	P	SO_2	DC	Electrochemical
INT	4000/LD/RM Series	R/F	SO_2	AC/DC	Electrochemical

Configuration: P = Personal, R = Portable, T = Transportable, F = Fixed

TABLE 4. Multigas Monitors

Manufacturer	Model	Configuration	Maximum Number of Sensors	Non-Specific Sensor	Gases	Specific Sensor	Number of Gases	Power	Detector
AGI	Micro 3000	R	4	Yes	Organic/Inorganic	No	NA	AC/DC	GC with 4 TCDs
AIM	9050	F	1	Yes	NH_3, NO, NO_2, SO_2, Cl_2, ClO_2, BTX; ppm	No	NA	AC	UV source
AIM	6200	F	1	Yes	NO_x, NO, NO_2, H_2O, SO_2, C_xH_y, CH_4, HCl, HF, CO, CO_2; ppm	No	NA	AC	IR (nondispersive)
AIM	5600	F	1	Yes	Same as model 9050 plus HONO; ppb - ppm	No	NA	AC	UV with differential optical absorption spectroscopy
AIM	8500	T	1	Yes	Model 9050 analytes plus HONO, O_3, H_2O_2, SO_3; ppb-ppm	No	NA	AC	UV with differential optical absorption spectroscopy
AIM	8647A	T	4	Yes	CO, CO_2, total hydrocarbons, NO; ppm	No	NA	AC	IR and UV with differential optical absorption spectroscopy
BIO	Toxi Vision EX	R	1	Yes	Combustible gases	No	NA	DC	Catalytic bead
BRU	E2M	R	1	Yes	Organic	No	NA	DC	GC-MS
BRU	Em640S	T	1	Yes	Organic	No	NA	DC	GC-MS
BRU	MM 2	R	1	Yes	Organic	No	NA	DC	GC-MS
BRU	OPAG	T	1	Yes	Organic	No	NA	DC	Remote sensing by FTIR
BRU	Raid-M series	R	1	Yes	TICs, CWAs; ppb to several ppm	No	NA	DC	ECD (^{63}Ni)
BRU	RAPID	R	1	Yes	TICs, CWAs; ppb to several ppm	No	NA	DC	Remote sensing by FTIR
BWT	GasAlertMicro 5 IR	P	5	Yes	CO_2, CO, O_2, H_2S, SO_2, NH_3, O_3, combustible gases; ppb - high ppm	Yes	12	DC	IR/electrochemical/ catalytic

TABLE 4. Multigas Monitors (Cont.)

Manufacturer	Model	Configuration	Maximum Number of Sensors	Non-Specific Sensor	Gases	Specific Sensor	Number of Gases	Power	Detector
CEA	AUTOFIM II	R	1	Yes	Hydrocarbons	No	NA	DC	FID
CEA	GASMAN	P	1	Yes	Flammable plus 17 other gases (single gas monitor); ppm	Yes	17	DC	Electrochemical
CEA	GASMAN II	P	1	Yes	Combustible plus 11 other gases; ppm	Yes	11	DC	Electrochemical
CEA	K850/KG850	R	2	Yes	General purpose; O_2 sensor available for KG850	Yes	NA	DC	Thermal conductivity (K850); KG850 has additional electrochemical sensor for O_2
CEA	Series U	R and F	1	Yes	Hydrocarbons	Yes	7	AC/DC	Photometric
CEA	SLEUTH	T	1	Yes	Hydrocarbons; ppm - ppb	No	NA	DC	FID
CEA	Spygas GAS	R	1	Yes	Flammable	No	NA	DC	Semi-conductor
CEA	TGM555	R	1	No	NO_2; HCl, N_2H_4, HF, Cl_2, H_2O_2; SO_2; HCHO; H_2S; HCN; NH_3 (list not inclusive); low ppm - ppb	Yes	19	AC/DC	Colorimetric, different modules for different analyte
CON	CT-1128	T	1	Yes	Organic	No	NA	DC	GC-MS
CDI	Detective +	T	4	Yes	VOC/Flammable, toxic; ppm	Yes	15	DC	IR
CDI	Eikon	P	1	No	NH_3, H_2S, CO, Cl_2, or O_2 deficiency; ppm	Yes	5	DC	Not specified
CDI	Triple Plus+	R	4	Yes	Flammable, toxic	Yes	7	DC	IR
CSE	Explorer 4	P	4	No	O_2, combustible, choice of two toxics: CO, H_2S, SO_2, NO, NO_2; ppm	Yes	6	DC	Electrochemical and pellistor (for combustibles)
DRA	PAC III	P	1	No	NA	Yes	50	DC	Electrochemical

TABLE 4. Multigas Monitors (Cont.)

Manufacturer	Model	Configuration	Maximum Number of Sensors	Non-Specific Sensor	Gases	Specific Sensor	Number of Gases	Power	Detector
ENM	EX-2000	P	1	Yes	Combustible hydrocarbons	No	NA	DC	Heat of combustion (catalytic)
ENM	RECON/4	P	1	No	CO, H_2S, O_2, combustible	Yes	3	DC	Electrochemical, catalytic
ENM	TX2000	P	1	No	Cl_2, H_2S, CO, NO, NO_2, NH_3, HCN, H_2, or O_3; ppm	Yes	9	DC	Electrochemical
ENV	ChemPro100	R	7	Yes	TIC/TIM, CWAs, VOCs	Yes	2	DC	Ion mobility, 2 semiconductor, field effect (FE), 3 MOS (metal oxide sensor)
ENV	ID-100	R	1	Yes	Organic/Inorganic	No	NA	DC	FTIR
ESC	Infrared Series Monitors	R	1	Yes	Hydrocarbons	Yes	3	DC	IR (nondispersive)
ESS	ecoSys-P	R	1	Yes	Organic/Inorganic	No	NA	AC/DC	MS
FEM	Environmental Vapor Monitor (EVM II)	R	1	Yes	Organic	No	NA	DC	Transfer line GC/Ion mobility
GFG	Exotector G600	R	1	Yes	Combustible gases	No	NA	DC	Catalytic combustion/thermal conductivity
GFG	G460	R	6	Yes	O_2, H_2S, CO, NH_3, SO_2, Cl, PH_3, NO_2, HCN, ETO, ClO_2, HF, NO, H_2; CO_2; VOCs	Yes	NA	DC	Electrochemical, NDIR for CO_2, PID for VOCs
GAT	400/450	T	1	Yes	Organic	No	NA	DC	GC-MS (ion trap)
HON	ChemKey TLD	R	1	No	See website	Yes	50	DC	Photometric (Chemcassette®)
HON	CM4	T	1	No	See website	Yes	25	AC	Photometric (Chemcassette®)
HON	Lumidar MiniMax XP	P	1	No	O_2, CO, H_2S, Cl, HCN, NO_2, NH_3, SO_2, or H_2	Yes	9	DC	Electrochemical

TABLE 4. Multigas Monitors (Cont.)

Manufacturer	Model	Configuration	Maximum Number of Sensors	Non-Specific Sensor	Gases	Specific Sensor	Number of Gases	Power	Detector
HON	Lumidar MiniMax XT	P	1	No	O_2, CO, or H_2S	Yes	3	DC	Electrochemical
HON	MST Satellite	R	1	No	See website	Yes	38	DC	Electrochemical
HON	MSTOX 9001	P	1	No	See website	Yes	24+	DC	Electrochemical
HON	Searchline Excel	F	1	Yes	Combustible gases	No	NA	DC	Xe Photometer
HON	SPM	R	1	No	See website	Yes	50	DC	Photometric (Chemcassette®)
HOR	APHA-370	T	1	Yes	Hydrocarbons	Yes	6	AC	FID
INF	Hapsite	R	1	Yes	Organic	No	NA	DC	GC-MS
ION	Ortho TOF	R	1	Yes	Organic	No	NA	DC	MS (time of flight)
ISC	GasBadge Pro	P	1	No	O_2, SO_2, Cl_2, ClO_2, NH_3, CO/H_2 null, H_2S, HCN, NO_2, PH_3, or SO_2; ppb-ppm	Yes	11	DC	Electrochemical
KAN	Aeroqual Series 500	P	1	Yes	O_3, NH_3, CO, H_2O_2, H_2S, NO_2, SO_2, or VOCs	Yes	NA	DC	Electrochemical
KOR	MS-200	R	1	Yes	Organic	No	NA	DC	MS (time of flight)
MAT	8066 Leak Hunter Plus	R	1	Yes	General purpose leak detector	No	NA	DC	Thermal conductivity
MAT	8057A	P	1	Yes	General purpose leak detector	No	NA	DC	Thermal conductivity
MAT	IQ1000	R	4	No	See website	Yes	140+	DC	Solid state, Electrochemical, Catalytic bead
MIC	ChemCube/ ChemPack	T	1	Yes	Organic	No	NA	DC	MS
MSA	Altair	P	1	No	CO, H_2S, O_2	Yes	3	DC	Electrochemical
MSA	Altair Pro	P	1	No	NA	Yes	10	DC	Electrochemical
MSA	Orion Plus IR	R	4	Yes	Hydrocarbons or CO_2, flammable, toxic, O_2	Yes	NA	DC	IR, Catalytic combustion, Electrochemical

TABLE 4. Multigas Monitors (Cont.)

Manufacturer	Model	Configuration	Maximum Number of Sensors	Non-Specific Sensor	Gases	Specific Sensor	Number of Gases	Power	Detector
MSA	Altair 5	R	2	Yes	Flammable, toxic	Yes	NA	DC	Catalytic combustion, Electrochemical
PHO	Voyager	R	1	Yes	VOCs	No	NA	AC/DC	GC with PID or ECD
PID	Hnu 301-C NEMA 4	F	1	Yes	Organic/Inorganic	No	NA	AC	GC with PID, FID, TCD, CCD, FPD, or FUV
PID	Hnu 312	R	1	Yes	Organic/Inorganic	No	NA	AC	GC with PID, FID, TCD, CCD, FPD, or FUV
PID	Hnu DL102	R	1	Yes	VOC/Inorganic gases	Yes	12	DC	PID, Electrochemical, TCD, IR, RH
RAE	BadgeRAE	P	1	No	NA	Yes	2	DC	Photometric
RAE	MiniRAE 2000	R	1	Yes	VOCs	No	NA	DC	PID
RAE	MultiRAE Plus	P	5	Yes	VOCs (0.1 ppm), Combustible gases, toxic, O_2	Yes	NA	DC	PID, Electrochemical
RAE	ToxiRAE 3	P	1	No	NA	Yes	2	DC	Photometric
RAE	ToxiRAE II	P	1	No	NA	Yes	11	DC	Photometric (sensors not interchangeable)
RAE	ToxiRAE Plus PID	R	1	Yes	VOC/Inorganic gases (low ppm)	No	NA	DC	PID
RAE	VRAE	R	5	Yes	Combustible, O_2, toxic	Yes	10	DC	Catalytic, Thermal conductivity, Electrochemical
RAI	NGA FID Hydrocarbon Analyzer Module	F	1	Yes	Hydrocarbons	No	NA	AC/DC	FID
RKI	Eagle	R	6	Yes	Combustible gases	Yes	21	DC	IR
RKI	GasWatch2	P	1	No	O_2, H_2S, or CO	Yes	3	DC	Electrochemical
RKI	GP-01	P	1	Yes	Combustible gases	No	NA	DC	Catalytic combustion
RKI	GX-82A	R	3	Yes	Combustible gases	Yes	1	DC	Catalytic, Electrochemical, Galvanic cell

TABLE 4. Multigas Monitors (Cont.)

Manufacturer	Model	Configuration	Maximum Number of Sensors	Non-Specific Sensor	Gases	Specific Sensor	Number of Gases	Power	Detector
RKI	RI-413A	R	1	Yes	Halocarbons	No	NA	DC	IR
RKI	RI-415	R	1	Yes	Hydrocarbons	No	NA	DC	IR
RKI	RX-415	R	2	Yes	Hydrocarbons	Yes	1	DC	NDIR
RKI	SC-01	P	1	No	NH_3, AsH_3, CO, Cl_2, H_2S, PH_3, or SO_2	Yes	7	DC	Electrochemical
SPE	C-21	P	1	Yes	VOCs	No	NA	DC	Heated semiconductor sensor
SRI	310/8610C	R	4	Yes	Organic	No	NA	AC/DC	GC with FID, PID, ECD, DEICD, TCD, NPD, FPD, HID
TFS	51C	T	1	Yes	VOCs	No	NA	AC	FID
TFS	580B	R	1	Yes	VOC/Inorganic gases	No	NA	DC	PID
TFS	MIRAN SapphIRe	R	1	Yes	VOCs	No	NA	DC	IR
TFS	55C	T	1	Yes	VOCs	No	NA	AC	GC/FID
TFS	ProTrace	F	3	Yes	Organic/Inorganic	No	NA	AC	GC with FID, TCD, and the ultra-high sensitivity pulsed discharge detectors
TFS	TVA1000B	R	2	Yes	VOC/Inorganic gases	No	NA	DC	PID/FID
VAR	4900-Micro C	T	1	Yes	Organic/Inorganic	No	NA	DC	Differential Mobility Detector

TABLE 5. Summary Information on Detectors and Instruments Used for On-site Monitoring of Gases and Vapors

Detector Type	Advantages	Limitations
Electrochemical	Good sensitivity, wide measurement range, low power requirements, low cost	Non-selective, restricted temperature range, affected by other gases
Semiconductor	Long life, relatively inexpensive, easy to use, can be used in O_2-deficient atmosphere	Non-selective, low sensitivity, temperature and humidity dependent, slow response and recovery (re-zero)
Conductivity – gold film	High selectivity and sensitivity, easy to use, rugged for field use	High cost, limited to H_2S and Hg vapor, gold film needs regular cleaning
Flame ionization	Long detector life, good sensitivity, continuous measurement, easy to use	Cannot differentiate between gases, requires H_2 supply (hazard), halogens ruin detector
Photoionization	Continuous measurement, easy to use/calibrate, rapid response, sensitive	Non-specific, cannot ionize some gases, sensitive to water, O_2 quenches response
Electron capture	Good sensitivity, long detector life, extremely sensitive to halogenated compounds	Only detects gases with electronegative atoms, non-specific, relatively expensive
Infrared	Good accuracy if interferences absent, sub-ppm detection limits, applicable to range of gases, non-poisonable, operating range sub-ppm to a few percent, single-species or multigas devices	High cost, bulky, relatively complex, not applicable to gases with little infra-red absorption
UV-VIS photometers	Detection limits sub-ppm to ppm, can be analyte specific (e.g., Hg vapor, O_3, SO_2, NO_x, NH_3, organic vapors)	Spectra interferences, primarily area monitors
Chemiluminescence	Detection limits 10 ppb, highly sensitive and selective for some gases (e.g., ozone, NO_x)	Relatively expensive, requires O_2 or O_3 generator (hazard), can be prone to interferences
Fluorescence	CO, SO_2, sulfur compounds, halogenated hydrocarbons, phosphorus compounds, etc.	Measurement in ppb to ppm range, depending on type; single- and multi-species devices
Flame Photometric	Low ppb detection limits, highly sensitive and selective for organosulfur and organophosphorus compounds	Very limited linear range

TABLE 5. Summary Information on Detectors and Instruments Used for On-site Monitoring of Gases and Vapors (Cont.)

Detector Type	Advantages	Limitations
Spectral intensity	Differentiates halogenated from nonhalogenated compounds	Detection limits in tens of ppm range, limited selectivity, cannot differentiat between halogenated compounds, different response curve for each halogenated compound
Paper tape (other photometric)	High selectivity, good sensitivity, fast response and recovery	High cost, limited range of tapes, short tape shelf life (3 months)
Detector tubes (see Chapter 17, ASI Manual, 9th Ed.)	Low cost, easy to use, wide range of gases	Limited accuracy, mainly for spot tests (some long-term tubes available), glass tubes must be disposed after use
Thermal conductivity	Long detector life, easy to use	Cannot distinguish different gases, limited range of gases
Heat of combustion (catalytic pellistor)	Low cost, simple operation, good lifespan, hazardous area approved	Non-specific, easily poisoned, detects flammable gases only, low sensitivity
Gas chromatography	Separates gas mixtures; good selectivity, accuracy, and sensitivity; long detector life; variety of detectors available	Not continuous, relatively long analysis time, requires carrier gas and skilled operator
Ion mobility spectrometer	High selectivity and sensitivity, fast response, hand-held detectors available, easy to use	Small range of detectable gases, high cost, humidity and temperature sensitive, small measuring range, some use radioactive source
Mass spectrometry	High accuracy, good sensitivity, high selectivity, long life, equipment can be designed for volatiles only (e.g., Inficon, Inc. HAPSITE, 35 lbs) or for full chemical analysis (e.g., Bruker VIKING 573, 86 lbs)	High initial and operating costs; complex–requires trained operator; spectral interference can occur if excessive water vapor present; relatively high concentrations of petroleum-based fuels in sample may require sample dilution and preclude analysis of analytes of interest

TABLE 6. Suppliers of Direct-reading Instruments for Gases and Vapors (Three-letter codes correspond to suppliers listed in preceding tables.)

AGI	Agilent Technologies, Inc. Headquarters 5301 Stevens Creek Blvd Santa Clara, CA 95051 (408) 345-8886 or (877) 424-4536 Fax: (408) 345-8474 http://www.agilent.com	BAC	Bacharach, Inc. 621 Hunt Valley Circle New Kensington, PA 15068-7074, USA (724) 334-5000 or (800) 736-4666 Fax: (724) 334-5001 http://www.bacharach-inc.com	CDI	Crowcon Detection Instruments Ltd. 21 Kenton Lands Road Erlanger, KY 41018-1845 (800) 527-6926 (800-5-CROWCON) Fax: (859) 957-1044 http://www.crowcon.com
AIM	Air Instruments & Measurements, LLC 15404 E. Valley Blvd City of Industry, CA 91746 USA Tel: (626) 330-4700 Fax : (626) 330-4776 http://www.aimanalysis.com	BIO	Biosystems, Inc. 651 South Main St. Middletown, CT 06457 (860) 344-1079 Fax: (860) 344-1068 http://www.biosystems.com	CEA	CEA Instruments, Inc. 16 Chestnut Street Emerson, NJ 07630 USA (201) 967-5660 or (888) 893-9640 Fax: (201) 967-8450 http://www.CEAinstr.com
AMK	AMKO Systems, Inc. 250 West Beaver Creek Rd., Unit 6 Richmond Hill, Ontario, L4B 1C7 Canada (905) 771-1444 Fax: (905) 771-1616 http://www.amkosystems.com	BRU	Bruker Daltonics Inc. 40 Manning Road Billerica, MA 01821 USA (978) 663-3660 Fax: (978) 667-5993 http://www.bdal.com	CON	Constellation Technology Corporation 7887 Bryan Dairy Road, Ste 100 Largo, FL 33777-1452 (800) 335-7355 or (727) 547-0600 Fax: (727) 545-6150 http://www.contech.com
AZI	Arizona Instrument LLC 1912 W. 4th Street Tempe, AZ 85281 (602) 470-1414 or (800) 528-7411 http://www.azic.com	BWT	BW Technologies America 3279 West Pioneer Parkway Arlington, TX, USA 76013 (817) 274-2487 or (888) 749-8878 Fax: (817) 274-8321 http://www.gasmonitors.com	CSE	CSE Corporation 600 Seco Road Monroeville, PA 15146 (800) 245-2224 Fax: (412) 856-9203 http://www.csecorporation.com
DRA	Draeger Safety Inc. 101 Technology Drive Pittsburgh, PA 15275-1057, USA (412) 787 8383 Fax: (412) 787 2207 http://www.draeger.com	ESS	European Spectrometry Systems Ltd. GeneSys House, Denton Drive Northwich, Cheshire CW9 7LU UK +44 (0) 1606 49400 Fax: +44 (0) 1606 330937 http://www.essco.com	HON	Honeywell Analytics Distribution Inc. 405 Barclay Boulevard Lincolnshire IL 60069 USA (847) 955-8200 or (800) 538-0363 Fax: (847) 955-8208 http://www.honeywellanalytics.com/
ENM	Enmet Corporation P.O. Box 979 Ann Arbor, MI 48106-0979 (734) 761-1270 Fax: (734) 761-3220 http://www.enmet.com	FSC	FemtoScan Corporation 747 East South Temple, #101 Salt Lake City, UT 84102 USA (801) 530-7117 Fax: (801) 322-1160 www.femtoscan.com	HOR	Horiba Instrument Corp. U.S. Headquarters 17671 Armstrong Ave. Irvine, CA 92614 (949) 250-4811 Fax: (949) 250-0924 http://www.horiba.com

TABLE 6. Suppliers of Direct-reading Instruments for Gases and Vapors (Three-letter codes correspond to suppliers listed in preceding tables.) (Cont.)

ENV	Environics, Inc. 69 Industrial Park Road East Tolland, CT 06084-2805 USA (860) 872-1111 Fax: (860) 870-9333 http:www.environicsusa.com/	GAT	Griffin Analytical Technologies 3000 Kent Avenue West Lafayette, IN 47906 (765) 775-1701 or (888) 775-1701 Fax: (765) 496-6489 http://www.griffinanalytical.com	INF	INFICON Two Technology Place East Syracuse, NY 13057 USA (315) 434-1100 Fax: (315) 437-3803 http://www.inficon.com
ESC	Environmental Sensors Company 3201 North Dixie Highway Boca Raton, FL 33431 (561) 338-7148 or (561) 338-3116 Fax: (561) 338-5737 http://www.environmentalsensors.com	GFG	GfG Instrumentation, Inc. 1194 Oak Valley Drive, Suite 20 Ann Arbor, MI 48108 USA (734) 769-0573 or (800) 959-0329 Fax: (734) 769-1888 http://www.gfg-inc.com	ION	Ionwerks, Inc. 3401 Louisiana, Suite 355 Houston, TX 77002 USA (713) 522-9880 Fax: (713) 522-6735 http://www.ionwerks.com
ISC	Industrial Scientific Corporation 1001 Oakdale Road Oakdale, PA 15071-1500 USA (412) 788-4353 or (800) 338-3287 Fax: (412) 788-8353 http://www.indsci.com	MIC	Microsaic Systems Limited GMS House Boundary Road Woking, Surrey GU21 5BX UK +44 [0]1483 751 576 or +44 [0]1483 751 577 Fax: 44 [0]1483 757 901 http://www.microsaic.com	QST	Quest Technologies Inc. 1060 Corporate Center Drive Oconomawac, WI 53066 (262) 567-9157 or (800) 245-0779 http://www.quest-technologies.com
KAN	Kanomax USA, Inc. 219 Route 206, PO Box 372 Andover, NJ 07821 (973) 786-6386 or (800) 247-8887 Fax: (973)-786-7586 http://www.kanomax-usa.com	MSA	Mine Safety Appliances Company 121 Gamma Drive Pittsburgh, PA 15238 (412) 967-3438 or (800) 672-4678 Fax: (412) 967-3235 http://www.msanet.com	RAE	RAE Systems, Inc. 3775 North First Street San Jose, CA 95134 USA (408) 952-8200 or (877) 723-2878 Fax: (408) 952-8480 http://www.raesystems.com
KOR	Kore Technology Ltd. Cambridgeshire Business Park Ely, Cambridgeshire CB7 4EA UK +44 (0) 1353 653030 Fax: +44 (0) 1353 653031 http://www.kore.co.uk	PHO	Photovac, Inc. 300 Second Avenue Waltham, MA 02451 (781) 290-0777 Fax: (781) 290-4884 http://www.photovac.com	RAI	Rosemount Analytical Inc. – Gas Division 6565 Davis Industrial Pkwy Solon, OH 44139 (440) 914-1261 or (800) 433-6076 Fax: (440) 914-1262 http://www.emersonprocess.com/raihome/
MAT	Matheson Tri-gas Inc. 166 Keystone Drive Montgomeryville, PA 18936 (215) 641-2700 or (800) 828-4313 Fax: (215) 619-0458 http://www.mathesontrigas.com	PID	PID Analyzers, LLC 780 Corporate Park Drive Pembroke, MA 02359 (508) 660-5001 or (800) 724-5600 Fax: (508) 660-5040 http://www.hnu.com	RKI	RKI Instruments, Inc. 33248 Central Ave. Union City, CA 94587 (510) 441-5656 (800) 754-5165 Fax: (510) 441-5650 http://www.rkiinstruments.com

TABLE 6. Suppliers of Direct-reading Instruments for Gases and Vapors (Three-letter codes correspond to suppliers listed in preceding tables.) (Cont.)

SEN	Sensidyne, Inc. 16333 Bay Vista Drive Clearwater, FL 33760 USA (727) 530-3602 or (800) 451-9444 Fax: (727) 539-0550 http://www.sensidyne.com	TEL	Teledyne Technologies Inc. 35 Inverness Drive East Englewood, CO 80112 (303) 792-3300 Fax: (303) 799-4853 http://www.teledyne-ml.com	VAR	Varian, Inc. 3120 Hansen Way Palo Alto, CA 94304-1030 USA (650) 213-8000 or (800) 926-3000 http://www.varianinc.com
SMC	Sierra Monitor Corporation 1991 Tarob Court Milpitas, CA 95035 (408) 964-4428 Fax: (408) 964-4420 http://www.sierramonitor.com	TES	Testo, Inc. 40 White Lake Road Sparta, NJ 07871 (862) 354-5001 (800) 227-0729 Fax: (862) 354-5020 http://www.testo.com	VIC	VICI Metronics, Inc. 26295 Twelve Trees Poulsbo, WA 98370 (360) 697-9199 or (877) 737-1887 Fax: (360) 697-6682 http://www.vici.com
SPE	Spectrex Corporation 3580 Haven Avenue Redwood City, CA 94063 (650) 365-6567 or (800) 822-3940 Fax: (650) 365-5845 http://www.spectrex.com	TFS	Thermo Fisher Scientific Air Quality Instruments 27 Forge Parkway Franklin, MA 02038 USA (978) 232-1037 or (888) 777-1954 Fax: (978) 232-6015 http://www.thermo.com		
SRI	SRI Instruments 20720 Earl St. Torrance, CA 90503 USA (310) 214-5092 Fax (310) 214-5097 http://www.srigc.com	TSI	TSI Incorporated 500 Cardigan Road Shoreview, MN 55126 USA (651) 490-2811 or (800) 874-2811 Fax: (651) 490-3824 http://www.tsi.com		

(List not inclusive)

DEPARTMENT OF HEALTH & HUMAN SERVICES

National Institute for
Occupational Safety and Health (NIOSH)

Memorandum

Date: June 11, 2009

From: Chief, Laboratory Research Branch, DRDS

Subject: Reprint of Publication

To: Joseph Burkhart
Deputy Director, DRDS

Attached is a reprint of a monograph I co-authored which was recently published electronically by the American Conference of Governmental Industrial Hygienists (ACGIH®). This monograph will be included in a future ACGIH *Signature Publication* that will be entitled: ACGIH ASI Manual: Air Sampling Technologies: Principles and Applications; Editor: David Leong. The DRDS clearance number is 2009-017B. It is provided for your review and retention.

REFERENCE
Birch ME, Pearce TA, Coffey CC. Direct-Reading Instruments to Gas and Vapor Detection [Online] Available at http://www.acgih.org/store/ProductDetail.cfm?id=2084 (Accessed on June 10, 2009).

Christopher C Coffey

Christopher C. Coffey

Attachments

cc:
Director, EID (3)
Librarian, Morgantown Branch (2)
Chief, FSB, DRDS (1)
Chief, SB, DRDS (1)