

# Specification and Selection of Hand-held Gas Monitors (Detectors) for Underground Mines

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## ABSTRACT

There are many sources of gas in underground mines including development and production blasting, strata gases, spontaneous combustion, diesel equipment, chemicals used for a wide range of functions, welding activities and fires.

It is only in relatively recent times that electronic gas monitors (or detectors) have become both safe and affordable for routine use.

In modern mines, gas monitors should be in daily use by the ventilation department as well as blasting re-entry (or clearance) crews, and are often used by drilling crews, shift supervisors, hygienists and mine rescue or fire fighting crews.

When first released, electronic gas monitors needed to be sent off-site periodically for calibration at a suitable accredited laboratory. Between calibrations, their accuracy was unknown. More recently, 'bump testing' and field calibration has become possible on the mine site, improving both reliability and safety as well as reducing the total number of gas monitors that need to be in use.

There has been almost an overwhelming increase in the number and sophistication of gas monitor features in recent years. This paper reports on a case study into the key criteria that ventilation practitioners should be aware of with respect to the specification and selection of the most recent gas monitoring systems, and recommends good practice for site-based operation and calibration.

## INTRODUCTION

There is a bewildering and at times conflicting amount of technical information regarding gas monitors currently available to the mine ventilation engineer. This paper sets out the key technical issues that ventilation engineers should be aware of prior to specifying and then evaluating gas monitors for their operating mine. It provides a series of criteria against which a new gas monitoring system could be reviewed for a mine, based on a case study.

## FLAMMABILITY AND TOXICITY ISSUES WITH REGARD TO SENSORS

It is important to note that there are three principal hazards from gases. All gases (except oxygen) are asphyxiating, ie in high concentrations they displace so much oxygen that the air is no longer safely breathable. In addition, some gases are toxic (harmful to human health, either in the short-term or long-term or both, even when in the presence of sufficient oxygen) and some are explosive. There are also several gases that are both toxic and explosive.

Even in hard rock mines, it is not uncommon to encounter the presence of flammable gases. Any gas that is flammable becomes explosive when mixed with air within certain concentration limits and then confined. If the volume of flammable gas within its explosive range is small, or the gas is not confined, then an ignition (eg a spark) will result in a

fire or deflagration (low pressure explosion). If the volume of explosive gas is larger and if it is constrained (eg in a tunnel) then it will become an explosion and the violence will progressively increase. If there is sufficient 'run-up' distance for the flame front of the flammable gas to accelerate, it will become a detonation (an explosion that travels above the speed of sound).

In hard rock mines, the following relatively common gases are all explosive: methane (CH<sub>4</sub>), hydrogen (H<sub>2</sub>), carbon monoxide (CO), hydrogen sulfide (H<sub>2</sub>S) and ammonia (NH<sub>3</sub>). This is not a complete list of all possible flammable gases in underground mines, but the other more common hard rock mine gases (O<sub>2</sub>, N<sub>2</sub>, CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>2</sub> and NO) are all *non-flammable* (Brake, 2015).

All flammable gases have a concentration in air below which the mixture is not flammable, and a concentration in air above which the mixture is not flammable. These two limits are called the 'lower explosive limit' (LEL) and 'upper explosive limit' (UEL). In most cases, the objective is to keep the concentration of flammable gas below its LEL, so it is the LEL that is generally more important in any practical sense than the UEL.

As noted above, some flammable gases are non-toxic. For example, methane is explosive but providing there is sufficient oxygen in the air, breathing air with methane in it does not

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cause any human ill-health effects. By contrast, some flammable gases are also toxic. The toxicity of a gas is given by its time weighted average (TWA), short-term exposure limit (STEL) and immediate danger to life and health (IDLH) values (all defined by the American Conference of Government Industrial Hygienists (ACGIH, 2015)) which are shown in Table 1 for the common flammable gases, along with the LEL and UEL values.

If a gas meter reads 'per cent LEL' it means the percentage of flammable gas in the air as a ratio of the LEL value for that flammable gas. For example, a reading of 20 per cent LEL would mean 20 per cent  $\times$  five per cent for methane (the LEL for methane is five per cent) or one per cent methane, assuming the LEL sensor has been calibrated using methane.

One important thing to note from this table is that if a gas is toxic, then it is usually only very low (ppm) concentrations that are needed for serious health effects but if the same gas is flammable then it is several per cent that is required for a hazard to exist. In other words, gases that are *both* toxic and flammable are usually of concern because they are toxic, whereas gases that are flammable but non-toxic are of concern because they are flammable or explosive. This distinction is important when understanding the correct selection of sensors for gas monitors.

In terms of preventing explosions, the purpose of a gas monitor is to detect a flammable gas irrespective of what flammable gas is present. In other words, the gas monitor should detect *any* explosive gas present, even if this is an unknown gas. In practice, this is strictly impossible; however, most flammable gases of interest in mines can be detected using a catalytic combustion sensor even when the actual gas is unknown.

## SENSORS

### Types of sensors

There are four principal types of sensors that are used in hand-held gas monitors (detectors). These are:

1. *Catalytic combustion (CC) sensors.* These will detect any flammable gas but cannot determine which flammable gas they have detected. They are designed for flammable but non-toxic gases, where the concentrations of interest are greater than about one per cent on a volumetric basis. They are usually calibrated using methane but this means their reading is less reliable if they are actually exposed to a different flammable gas. Fortunately, the response of CH<sub>4</sub> and H<sub>2</sub> (the two most important flammable gases in underground mines) to a CC sensor is relatively similar, especially since alarm levels are usually set at 20 per cent and 40 per cent of LEL (or direct readout in CH<sub>4</sub>). CC sensors are not suitable for measuring flammable gas concentrations above the LEL or for measuring in low oxygen environments (under ten per cent O<sub>2</sub>) (see later).
2. *Electrochemical (EC) sensors.* These are commonly used for toxic gases where the concentrations of interest are in the ppm range. Some EC sensors can measure two gases from the one sensor. The most common such arrangement is CO and H<sub>2</sub>S (the so-called 'COSH' or 'duo' sensor). Some of the gases of interest measured by EC sensors are both toxic and flammable (eg carbon monoxide) but in this case, the toxicity issue is far more important than flammability (eg CO is toxic at a few hundred ppm but only explosive at about 12.5 per cent or 125 000 ppm). EC sensors should not be used for CO<sub>2</sub> due to the severe time-related loss of accuracy.
3. *(Non-dispersive) Infrared (IR or NDIR) sensors.* These are used for carbon dioxide (as it cannot be reliably measured

by EC sensors) and also for reading the concentration of flammable gases *above* their LEL (usually up to 100 per cent flammable gas, eg for checking propane or methane concentrations in pipelines). They are also specific to a particular flammable gas; however, they cannot measure molecules that are not IR-active such as hydrogen.<sup>2</sup> Some IR sensors can read both ppm and high concentrations of the same gas at the same time. IR sensors are also used in atmospheres with low oxygen or in atmospheres that would poison a CC sensor (see later). IR sensors are more expensive than other types, but are poison-free and last much longer with fewer problems.

4. *Photo ionisation (PID) detectors (sensors).* These are used to measure so-called volatile organic compounds (VOCs), which are organic substances (those containing carbon) with a high vapour pressure and low water solubility such as diesel, gasoline, kerosene and other fuels, solvents, hydraulic fluids, paint thinners and dry-cleaning agents, etc commonly used in urban settings. These substances are both flammable and toxic at low concentrations. The industry standard is for PID sensors to be calibrated to isobutylene. Mine ventilation engineers are not usually concerned with measurement of VOCs.

The advantages and disadvantages of the various sensor technologies is summarised in Appendix 1. PID sensors have been excluded for reasons noted above.

### Sensors on hand-held monitors and number of gases that can be measured

The most recent multigas monitors have up to five sensor positions or 'channels'. However, typically one position is reserved (and only suitable) for an IR sensor and another is reserved (and only suitable) for a CC sensor with the remaining three (say) being available for EC and PID sensors (Table 2).

Since some sensors can measure two gases, it is therefore possible for a five-channel gas monitor to be able to measure seven gases. However, this would only be possible for a specific set of gases and not the general case. In fact, if the IR or CC channel is not needed for a gas of interest, then a five-channel gas monitor may only be able to measure three gases.

### Sensor combinations

Various specialist sensors or sensor combinations can be produced by manufacturers to cover specific situations. A small portion of the sensors available from one manufacturer is shown in Table 3. Examples include:

- dual sensors for combustible gases and CO<sub>2</sub>
- dual sensors for CO and H<sub>2</sub>S (COSH sensor)
- CO sensor with reduced H<sub>2</sub> sensitivity.

For this reason, it is important to carefully assess not only the gases that need to be measured, but any other gases that may be present either in normal or in abnormal conditions, to allow the supplier to make the most appropriate recommendation for the sensor configuration.

### 'Plug and play' or 'plug-in' sensors

Most sensors have a life of one to three years (IR sensors can last five years or longer). At the end of this time they must be replaced. Plug and play or plug-in sensors refers to sensors that can be replaced by the user without returning the

2. In order for a molecule to be IR-active, the vibration must produce an oscillating dipole. This usually means that the bond (or bonds) in question are polar to begin with, so that they have a dipole. Therefore symmetrical molecules like O<sub>2</sub>, N<sub>2</sub> and H<sub>2</sub> are not IR active, but molecules like H<sub>2</sub>O with polar bonds are IR active (Anon, 2014b).

TABLE 1

Common flammable gases in underground mines, lower exposure limit, upper exposure limit and toxicity.

Flammable gas name	Methane	Hydrogen	Carbon monoxide	Hydrogen sulfide	Ammonia
Chemical symbol	CH <sub>4</sub>	H <sub>2</sub>	CO	H <sub>2</sub> S	NH <sub>3</sub>
Lower explosive limit (LEL)	5%	4%	12.5%	4.5%	15%
Upper explosive limit (UEL)	15%	74%	74%	45%	28%
Time weighted average (ppm)	Non-toxic	Non-toxic	30	2	25
Short-term exposure limit (ppm)	Non-toxic	Non-toxic	N/A but see Safe Work Australia (2012)	5	35
Immediate danger to life and health (IDLH) (ppm)	Non-toxic	Non-toxic	1200	100	300

TABLE 2

Example of sensor types and sensor position options for a 'seven gas' (five channel) gas monitor. This instrument can fit one catalytic combustion sensor, one infrared sensor, two electrochemical sensors and one photo ionisation or electrochemical sensor to its five sensor positions (source: GfG Operation Manual Microtector II G460).

Sensor type		Sensor position				
Test gas	Range	1	2	3	4	5
Ammonia NH <sub>3</sub>	0–200 ppm	EC	EC	EC		
Flammable gases: methane, propane, hexane, nonane	0–100 % LEL				CC	IR
Chlorine Cl <sub>2</sub>	0–10 ppm		EC	EC		
Chlorine dioxide ClO <sub>2</sub>	0–2 ppm		EC	EC		
Hydrogen chloride HCl	0–30 ppm	EC	EC	EC		
Ethylene oxide C <sub>2</sub> H <sub>4</sub> O	0–20 ppm		EC	EC		
VOC – isobutylene C <sub>4</sub> H <sub>8</sub>	0–500 ppm		PID			
VOC – isobutylene C <sub>4</sub> H <sub>8</sub>	0–2000 ppm		PID			
Carbon dioxide CO <sub>2</sub> and methane	0–5 % vol 0–100% LEL 0–100% LEL					IR

VOC – volatile organic compounds; LEL – lower exposure limit; EC – electrochemical; CC – catalytic combustion; IR – infrared; PID – photo ionisation detector.

monitor to the factory and without any need for soldering. Plug and play sensors have their own integrated circuit board and are precalibrated so that when the old sensor is replaced, the monitor can obtain all the information about the new sensor from its onboard integrated circuit (IC) and the monitor is then ready for use. Plug-in sensors do not have an IC so that once they are installed, the sensor identity code must be manually programmed into the monitor using supplied software (ie the monitor must be told that the new sensor is a certain type with certain range, etc). This is also a simple exercise. Both systems mean that when the sensor's life has expired (and the monitor will advise the user of this), then a new sensor can be quickly and easily installed into the monitor on-site. Since multigas monitors may have up to five sensors, and the sensors for each gas have a finite life and do not expire together, conventional multigas monitors without field-replaceable sensors do, in fact, need to be off-site for substantial periods, probably requiring double the number of monitors to be purchased as is needed at any time. Field-replaceable sensors eliminate this problem.

### Factors affecting accuracy or damage to sensors

*Poisoning* of a sensor occurs if it is exposed to a substance that damages it. Poisoning can be either permanent or reversible (usually with some after-treatment). Catalytic sensors can be poisoned temporarily or permanently by compounds containing halogens, sulfur, chlorine, lead or silicones.

*Sooting* refers to a temporary condition experienced by flammable gas detectors that are used in atmospheres above

the LEL for that gas for a period of time. This will affect the accuracy of the instrument but is usually a temporary condition that will be cleared as the instrument is operated outside of the explosive range. Some CC sensors will automatically shut down when above the LEL (after alarming) to prevent more serious damage to the sensor.

*Cross-sensitivity* (or *interference*) refers to the fact that some sensors give a false indication when exposed to a substance other than the one of concern. For example, a catalytic combustion methane sensor calibrated for methane and reading one per cent methane will actually be measuring the following concentration if exposed to these cross-sensitive gases: ammonia 0.6 per cent; carbon monoxide 1.2 per cent; hydrogen 1.2 per cent. So, for example, if a catalytic combustion sensor calibrated for methane reads 95 per cent LEL (or reads 4.75 per cent CH<sub>4</sub>), but has actually been exposed to hydrogen (perhaps unknown to the person using the monitor), then the true reading of methane is NIL but the true reading of hydrogen is 1.2 × 4.75 per cent or 5.7 per cent H<sub>2</sub>. Note that the reading of 4.75 per cent implies the gas mixture is non-explosive (if it were CH<sub>4</sub>), but the true reading of 5.7 per cent H<sub>2</sub> is well above the LEL for H<sub>2</sub> of four per cent. This cross-sensitivity issue is much worse if the CC sensor calibrated to methane is used to measure (say) gasoline vapours. Sometimes the issue of cross-sensitivity is described in terms of *specificity*, which means the ability of a sensor to measure a particular gas and only that gas.

### Specific issues for underground mines

*Oxygen sensor*: oxygen sensors are sensitive to rapid changes in barometric pressure. Hence it is common for them to alarm

TABLE 3

A small portion of the range of sensors available from one manufacturer (source: GfG Operation Manual Microtector II G460).

MK211-6	Sensor for 100% lower explosive limit (LEL) combustible gases and vapours
MK211-7	Sensor for 100% LEL combustible gases (with increased position resistance)
MK222-2	Isobutylene sensor, 500 ppm C <sub>4</sub> H <sub>8</sub>
MK222-3	Isobutylene sensor, 2000 ppm C <sub>4</sub> H <sub>8</sub>
MK224-5	Carbon dioxide sensor, 5 vol % CO <sub>2</sub> (infrared)
MK227-5	Sensor for combustible gases and vapours, 100% LEL CH <sub>4</sub> (infrared)
MK227-5	Sensor for combustible gases and vapours, 100% LEL + 100% vol CH <sub>4</sub> (infrared)
MK231-5	Dual-sensor for combustible gases and vapours, 100% LEL CH <sub>4</sub> and for carbon dioxide 5% vol CO <sub>2</sub> (infrared)
MK231-5	Dual-sensor for combustible gases and vapours, 100% LEL + 100% vol CH <sub>4</sub> and for carbon dioxide 5% vol CO <sub>2</sub> (infrared)
MK344-5	Carbon monoxide sensor, 300 ppm CO (no warning from H <sub>2</sub> S)
MK344-4	Carbon dioxide sensor, 500 ppm CO (no warning from H <sub>2</sub> S)
MK344-6	Carbon monoxide sensor, 1000 ppm CO (no warning from H <sub>2</sub> S)
MK346-5	Sulfur dioxide sensor, 10 ppm SO <sub>2</sub>
MK347-5	Nitrogen monoxide sensor, 100 ppm NO
MK348-5	Nitrogen dioxide sensor, 30 ppm NO <sub>2</sub>
MK353-5	Phosphine sensor, 10 ppm PH <sub>3</sub>
MK369-5	Carbon monoxide sensor, 300 ppm CO (reduced H <sub>2</sub> sensitivity)
MK369-6	Carbon monoxide sensor, 500 ppm CO (reduced H <sub>2</sub> sensitivity)
MK379-5	Ethylene oxide sensor, 20 ppm C <sub>2</sub> H <sub>4</sub> O
MK380-5	Dual sensor carbon monoxide, 500 ppm CO and hydrogen sulfide, 100 ppm H <sub>2</sub> S
MK383-5	Oxygen sensor, 25 % vol O <sub>2</sub> (two years)

if the gas monitor is taken down in the cage in a vertical shaft in a mine. For this reason, some manufacturers produce two oxygen sensors as standard. The shorter (eg two-year) life O<sub>2</sub> sensor is designed to stabilise far quicker than the longer (eg three-year life) sensor due to the size of the capillary hole through which the O<sub>2</sub> molecules diffuse into the sensor. However, this may still not be sufficient to avoid the O<sub>2</sub> sensor alarming in deep mines with vertical shafts and rapid cage movements. In this case, a special oxygen sensor with a built-in pressure vent allowing the sensor to rapidly adapt to pressure changes may be available.

*LEL (CH<sub>4</sub>) sensor:* some CH<sub>4</sub> sensors include silicon protection (a filter that absorbs silicon compounds in the atmosphere which prevents the sensor from losing sensitivity) as silicon compounds poison these types of catalytic combustion sensors. Some instruments also have over-limit protection for their CC sensors. Should high levels of combustible gas be detected and the sensor goes above a predefined value (eg 110 per cent of its LEL) the power to the active bead within the sensor is switched off to avoid permanent damage.

## Battery life

IR and CC sensors are both power intensive. However, ECs hardly draw any power, so the typical nickel metal hydride (NiMH) battery life for a monitor that has only EC sensors on it will be much longer (perhaps four years) compared to a monitor that has both an IR and a CC sensor on it (perhaps two years), due to the far fewer number of battery charge/discharge cycles for the instrument with EC-only sensors.

In addition, to ensure gas monitors are always available in an emergency, it is prudent to either have spare battery packs always on charge, or backup battery packs that can use disposable alkaline batteries.

## Alarm levels and latching alarms

Most monitors have at least a low alarm ('Alarm 1' or A1) and a high alarm ('Alarm 2' or A2). The A1 alarm is often *non-latching*, which means that if the monitor goes into low alarm but gas concentration then falls back below the A1 limit the alarm will automatically cancel itself. It is not uncommon for the A2 alarm to be a *'latching alarm'* which means that once triggered, the monitor will remain 'in alarm' until it is removed to an atmosphere below the A2 level and then manually reset. Obviously this is for safety reasons as the A2 alarm is indicating a dangerous situation whereas the A1 alarm is more for warning purposes.

Some monitors also trigger not only at A1 and A2 limits, but also continuously calculate TWA values (ie personal time-weighted doses) and will alarm when either the TWA or STEL is exceeded.

Alarms should always indicate via audible, visible and vibrating means so they cannot be overlooked in an underground environment that may have high noise and low light levels.

## Response time of sensors

There are several methods of rating the ability of a sensor to respond to its target gas in a timely manner. The t<sub>50</sub> (T-50) and t<sub>90</sub> (T-90) are the time (seconds) for the sensor to reach 50 per cent or 90 per cent respectively of the true gas concentration (see Figure 1 as an example). Unfortunately there are a number of ways in which these results can be (mis) represented so the user needs to take great care in comparing values from different manufacturers:

- Some manufacturers rate their sensors 'unmounted' (ie a bare or raw sensor *not fitted to the monitor*) and others rate them mounted into the gas monitor. An unmounted sensor can respond two to three times faster than a mounted

## Response of 4HSLM City Technology H<sub>2</sub>S sensor installed in G450 to 20 ppm H<sub>2</sub>S calibration gas (all standard filters left in place)

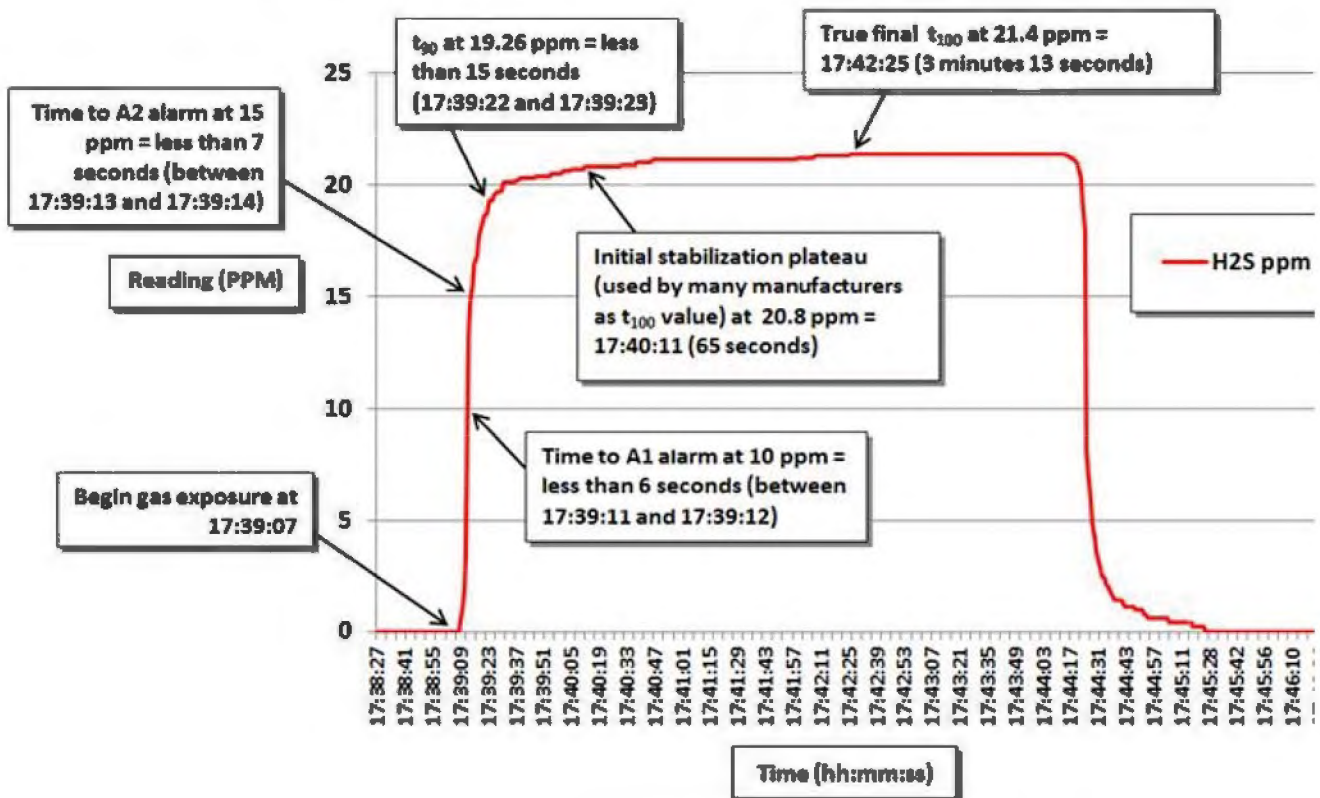


FIG 1 –  $T_{90}$  ( $t_{90}$ ) and 'time to alarm' for gas sensors (D Robertson, 2014, personal communication).

sensor but this difference is illusory as sensors are never, in fact, used in an unmounted state. When mounted, sensors need to be protected from water, etc using filters and this protection plus other factors increases the response time.

- Some manufacturers consider the time for the sensor response to be when it starts to respond. This is not correct as the gas will take one to two seconds to pass through the membrane over the sensor and this should be considered part of the response time. In other words, the start time should be measured from the time the monitor is exposed to the gas, not when the sensor first starts to read the gas.
- Some manufacturers consider the  $t_{100}$  time (ie time at which the sensor is considered to have responded) to be the initial plateauing of the sensor (where it has substantially levelled off, but is still increasing slowly), but others consider it to be where it has truly 'flat lined' (see Figure 1).
- Finally, the response times can be artificially shortened by reducing the resolution of data once graphed. Effectively this is a form of weighted-averaging (smoothing the response curve) and will reduce the  $t_{90}$  and  $t_{100}$  times, sometimes by a considerable margin.

Therefore, the best measure of response time is the 'time to alarm' for the gas monitor to a particular concentration of the target gas from the time the gas makes contact with the outside of the gas monitor when using an agreed resolution. This will obviously depend on the concentration of gas and the alarm set points. Other measures such as  $t_{90}$  may be useful for sensor manufacturers but are irrelevant and can be quite misleading for the end user.

### Range, operating limits, resolution, tolerance-band, accuracy and cross-sensitivity of sensors and sensor life

Refer to Figures 2, 3, 4 and Table 4.

In discussing the applicability of any ventilation instrument, including gas monitors, it is important to understand some fundamental terms:

- *Range* is the upper and lower measurement limits of the sensor.
- *Accuracy* is the ability of a sensor to give the correct (true) value.
- *Precision* is the ability of an instrument to give the same reading when exposed to the same concentration ... the reading may be wrong (inaccurate) but is consistent (precise)!
- *Repeatability* is much like precision but includes the ability of the instrument to return to reading nil values between measurements.
- *Resolution* is the smallest change in value that is recorded on the instrument's display.
- *Sensitivity* is usually considered to be the minimum value that can be detected or the 'limit of detection'.

The (detection) range of a gas sensor is the operating limits (ppm or per cent volume) that it can measure. For example, a manufacturer could supply CO sensors that are 0–100 ppm, 0–500 ppm or 0–10 000 ppm. It is usually desirable to have the smallest range that can meet the requirements both in normal use and most abnormal situations of interest. For example, most working places will need to keep CO concentrations below the TWA (30 ppm for eight hour shifts in Australia) or at the most, below the STEL (often taken as 90 ppm).

<b>MK211-6 Catalytic combustion sensor for combustible gases and vapours</b>			
Detection range:	0.0 .. 100%LEL		
Response time:	$t_{50}$ : $\leq 10$ sec	$t_{90}$ : $< 20$ sec for CH <sub>4</sub> (Methane)	$t_{50}$ : $\leq 12$ sec $t_{90}$ : $< 30$ sec f
		C <sub>3</sub> H <sub>8</sub> (Propane)	
	$t_{50}$ : $\leq 40$ sec	$t_{90}$ : $< 175$ sec for C <sub>6</sub> H <sub>14</sub> (n-Hexane)	
Pressure (70)80....120(130) kPa:	max. $\pm 5\%$ LEL of range or $\pm 10(15)\%$ of display (referred to 100 kPa)		
Humidity 0%...95% r.h.:	max. $\pm 7\%$ LEL of range or $\pm 10\%$ of display (referred to 0% r.h. @40°C)		
Temperature -20...+ 55°C:	max. $\pm 5\%$ LEL of range or $\pm 10\%$ of display (referred to 20°C)		
Cross sensitivities [¶] @ 50%LEL:	Gas supply	CH <sub>4</sub> display	C <sub>3</sub> H <sub>8</sub> display n-Hexane display
	2,00%Vol H <sub>2</sub>	ca.85%LEL	ca.105% LEL ca.140% LEL (theor.)
	2,20%Vol CH <sub>4</sub>	= 50% LEL	ca.60% LEL ca.80% LEL
	0,85%Vol C <sub>3</sub> H <sub>8</sub>	ca.41% LEL	= 50% LEL ca.66% LEL
	0,70%Vol C <sub>4</sub> H <sub>10</sub>	ca.39% LEL	ca.48% LEL ca.63% LEL
	0,70%Vol C <sub>4</sub> H <sub>12</sub>	ca.37% LEL	ca.44% LEL ca.58% LEL
	0,50%Vol C <sub>6</sub> H <sub>14</sub>	ca.27% LEL	ca.32% LEL = 50% LEL
	0,55%Vol C <sub>7</sub> H <sub>16</sub>	ca.22% LEL	ca.27% LEL ca.42% LEL
	0,55%Vol C <sub>8</sub> H <sub>20</sub>	ca.17% LEL	ca.22% LEL ca.35% LEL
	May vary from sensor to sensor and depend on the gas concentration and on the age of the sensor.		
Expected lifetime:	3 years in clean air		

FIG 2 – Specification for catalytic combustion sensor (source: GfG Operation Manual Microtector II G460).

<b>MK224-5/MK231-5 Infrared sensor for carbon dioxide CO<sub>2</sub></b>			
Detection range:	0.02 .. 5.0%Vol (25.0%Vol <sup>[¶]</sup> ) Zero point drift $\leq 0.03\%$ Vol		
Response time:	$t_{50}$ : $\leq 20$ sec	$t_{90}$ : $\leq 50$ sec	$t_{10}$ : $\leq 50$ sec (decay time @ CO <sub>2</sub> )
Pressure 70...130 kPa:	$< 1.6\%$ of display per 1% pressure change (referred to 100 kPa)		
Humidity 0%...95% r.h.:	max. $\pm 0.01$ Vol% or $\pm 2\%$ of display (referred to 50% r.h. @ 20°C)		
Temperature -20...+55°C:	max. $\pm 0.01$ Vol% or $\pm 10\%$ of display (referred to 20°C)		
Long term stability per month:	max. $\pm 0.01$ Vol% or $\pm 2\%$ of display (laboratory conditions)		
Expected lifetime:	6 years		

FIG 3 – Specification for infrared sensor (source: GfG Operation Manual Microtector II G460).

<b>MK344-4//5<sup>[¶]</sup> /-6<sup>[¶]</sup> Electrochemical sensor for carbon monoxide CO</b>			
Detection range:	2.. 5000ppm (300/1000ppm <sup>[¶]</sup> ) zero point drift $\leq 3$ ppm		
Response time:	$t_{50}$ : $< 20$ s	$t_{90}$ : $< 65$ s	$t_{10}$ : $< 70$ s (decay time)
Pressure (70)90...110(130) kPa:	max. $\pm 2$ ppm or $\pm 12(14)\%$ of display (referred to 100 kPa)		
Humidity 5%...95% r.h.:	max. $\pm 1$ ppm or $\pm 2\%$ of display (referred to 50% r.h. @ 20°C)		
Temperature -10(-20)...+40(55)°C:	max. $\pm 3(5)$ ppm or $\pm 5(10)\%$ of display (referred to 20°C)		
Long term stability <sup>[¶]</sup> per month:	max. $\pm 1$ ppm or $\pm 2\%$ of display (laboratory conditions)		
Cross sensitivities:	H <sub>2</sub> S $< 4\%$ ; C <sub>2</sub> H <sub>4</sub> $< 50\%$ ; H <sub>2</sub> $< 40\%$ ; NO $< 9\%$ ; NO <sub>2</sub> $< \pm 5\%$ ; SO <sub>2</sub> $= 0\%$ ; Cl <sub>2</sub> $= 0\%$ ; C <sub>2</sub> H <sub>6</sub> $= 0\%$ (*1)		
Expected lifetime:	3 years		

FIG 4 – Specification for electrochemical sensor (source: GfG Operation Manual Microtector II G460).

Concentrations in blasting fumes or low-level fires could be higher than this, so a CO sensor with a range of 0–500 ppm could be the appropriate choice. A CO sensor with range of 0–10 000 ppm is unlikely to be the appropriate choice for mine ventilation.

The operating limits are the range of temperatures, humidity and barometric pressures in which the instrument can be safely and accurately used. The barometric pressure, in particular, can be an issue for very deep underground mines or mines at very high altitude. The barometric pressure operating limits should always be converted to elevations above and below sea level and compared to the mine's operating levels.

The resolution of the instrument for that sensor is the smallest change in value that the instrument will measure and display. For example, in Table 4, the 0–500 ppm CO sensor will be able to be read to 1 ppm on the gas monitor display. However, most gas monitor manufacturers also provide a 'dead band' or other means of suppressing spurious noise in the instrument around its 'zero-air' value. For example, a manufacturer could have a 3 ppm dead band setting for CO, which would mean that the CO reading will not display CO readings of 1 or 2 ppm (ie will display these as being 0 ppm CO). This dead band setting should be able to be turned on/off by the user.

Some manufacturers implement this dead band concept as its tolerance band (T-band or TB). The T-band is partly a

dead band and partly a 'sticky filter'. As an example, if the default T-band value for CO is (say) 3 ppm (Table 4), then the monitor, once turned on and finished its start-up checks in nil-CO air, will not display CO values under 3 ppm. The filter is then progressively applied up to 200 per cent of the T-band value of 3 ppm = 6 ppm range. The stickiness filter is not applied to values higher than 6 ppm. The filter in this particular case works as follows:

- between 0 and 3 ppm the display will show a reading of 0 ppm
- at 4 ppm the display will show a reading of 2 ppm
- at 5 ppm the display will show a reading of 4 ppm
- at 6 ppm the display will show a reading of 6 ppm.

Note that the true (non-adjusted) CO values are still included in the dose measurements of TWA and STEL by the instrument.

Do not confuse dead band (or T-band) with accuracy. The accuracy of the instrument for that sensor is the spread of the true value around the actual value displayed on the instrument. In the case of 0–500 ppm CO (Figure 4), the accuracy for this sensor varies with temperature, pressure, humidity and also shows a time-related drift. For example, the CO reading will vary by  $\pm 2$  ppm or  $\pm 12$  per cent on the display (whichever is the lesser) for pressure changes from 90 to 110 kPa (from a baseline of 100 kPa) or  $\pm 2$  ppm or  $\pm 14$  per cent on the display (whichever is the lesser) for pressure changes from

TABLE 4

Sensor types, ranges, resolution and 'T(tolerance)-band' values (source: GfG Operation Manual Microtector II G460).

Slot	Sensor type	Detection range	Gas	Resolution	T-Band (*1)
EC1	MK380-5 <sup>[*]</sup>	0 ... 500 ppm	CO Carbon monoxide	1 ppm	±3 ppm
		0 ... 100 ppm	H <sub>2</sub> S Hydrogen sulfide	0.5 ppm	±1.5 ppm
EC1 EC2 EC3	MK344-4	0 ... 500 ppm	CO Carbon monoxide	1 ppm	±3 ppm
		0 ... 300 ppm	CO Carbon monoxide	1 ppm	±3 ppm
		0 ... 1000 ppm	CO Carbon monoxide	1 ppm	±5 ppm
		0 ... 10 ppm	SO <sub>2</sub> Sulfur dioxide	0.1 ppm	±0.2 ppm
		0 ... 10 ppm	PH <sub>3</sub> Phosphine	0.05 ppm	±0.05 ppm
		0 ... 300 ppm	CO Carbon monoxide	1 ppm	±3 ppm
		0 ... 500 ppm	CO Carbon monoxide	1 ppm	±3 ppm
		0 ... 25 vol %	O <sub>2</sub> Oxygen	0.1 vol %	±0.3 ppm
		0 ... 2000 ppm	CO Carbon monoxide	1 ppm	±4 ppm
		0 ... 200 ppm	NH <sub>3</sub> Ammonia	1 ppm	±3 ppm
		0 ... 2000 ppm	H <sub>2</sub> Hydrogen	2 ppm	±50 ppm
		0 ... 1000 ppm	NH <sub>3</sub> Ammonia	5 ppm	±10 ppm
		0 ... 1 vol %	H <sub>2</sub> Hydrogen	0.01 vol %	±0.02 vol %
		0 ... 4 vol %	H <sub>2</sub> Hydrogen	0.01 vol %	±0.05 vol %
		0 ... 40 ppm	SiH <sub>4</sub> Silane	0.1 ppm	±0.4 ppm
		0 ... 50 ppm	HCN Hydrogen cyanide	0.5 ppm	±1.5 ppm
		0 ... 25 vol %	O <sub>2</sub> Oxygen	0.1 vol %	±0.3 vol %
		0 ... 100 ppm	H <sub>2</sub> S Hydrogen sulfide	0.2 ppm	±1.0 ppm
		0 ... 500 ppm	H <sub>2</sub> S Hydrogen sulfide	0.5 ppm	±1.0 ppm
		EC2 EC3	MK347-5 <sup>[*]</sup>	0 ... 100 ppm	NO Nitrogen monoxide
0 ... 30 ppm	NO <sub>2</sub> Nitrogen dioxide			0.2 ppm	±0.6 ppm
0 ... 20 ppm	C <sub>2</sub> H <sub>4</sub> O Ethylene oxide			0.1 ppm	±0.3 ppm
0 ... 10 ppm	Cl <sub>2</sub> Chlorine			0.1 ppm	±0.1 ppm
0 ... 30 ppm	HCl Hydrogen chloride			0.2 ppm	±0.4 ppm
PID (EC2)	MK222-2 <sup>[*]</sup>	0 ... 500 ppm	C <sub>4</sub> H <sub>8</sub> Isobutylene	0.1 ppm	±0.3 ppm
		0 ... 2000 ppm	C <sub>4</sub> H <sub>8</sub> Isobutylene	0.5 ppm	±1.0 ppm
CC (PL)	MK211-6	0 ... 0.5 vol %	CH <sub>4</sub> Methane	0.02 vol %	±0.14 vol %
		0 ... 100% LEL	CH <sub>4</sub> Methane (*2)	0.5% LEL	±2.5% LEL
IR	MK224-5	0 ... 5 vol %	CO <sub>2</sub> Carbon dioxide	0.010, 0.5 vol %	-
		0 ... 100% LEL 0 ... 100% vol	CH <sub>4</sub> Methane (*2) s. below CH <sub>4</sub> Methane	0.2 ... 1.0% LEL 0.01 ... 0.5% vol	±1.2% LEL ±0.05 vol %
	MK231-5	0 ... 5% vol	CO <sub>2</sub> Carbon dioxide	0.01 ... 0.05 vol	-
		0 ... 100% LEL 0 ... 100% vol	CH <sub>4</sub> Methane (*2) CH <sub>4</sub> Methane	0.2 ... 1.0% vol 0.01 ... 0.5% vol	±1.2% LEL ±0.05 vol %

LEL – lower exposure limit.

70 to 130 kPa (from a baseline of 100 kPa). Note that these tend to be the extreme limits; most instruments are not required to operate between 70 and 130 kPa or over the temperature ranges quoted. However, under extreme conditions where temperature, humidity and pressure are all at their limits, the CO sensor could be up to about 10 ppm or 20 per cent of the displayed value away from the true value (accuracy limits are additive).

Figure 4 also shows the cross-sensitivity of this particular sensor to other common gases, as well as the sensor life. Note that the sensor life is being 'used up' not only when the monitor is turned on, but from the date that the sensor is fitted to the monitor and hence is exposed to air.

## Calibration of sensors

### Why is calibration necessary?

Calibration is necessary to avoid situations where:

- A sensor has become poisoned or access to it has been blocked or partially blocked. Calibration is the only way to detect this condition as in some cases the sensor still gives readings but these may not be reliable.
- As sensors age they begin to lose their calibration more quickly. Sensors older than one year need more frequent calibration to maintain their accuracy and to prevent false alarms.

- Calibration is often also necessary whenever a sensor is replaced.
- Calibration is also needed when the monitor is subject to being dropped or experiencing another significant impact, being exposed to water, failing a bump test or has been repeatedly exposed to an over-range gas concentration (positive or negative in the case of O<sub>2</sub>).

### Off-site (laboratory) calibration

In the past, electronic gas monitors were required to be returned to the manufacturer or an approved laboratory each year or more frequently for calibration and recertification. Apart from the costs, transport issues and additional monitors needed to cover the time the instruments were off-site, this meant that there was no certainty that the monitor was working correctly after it was returned to the user. Such a calibration strategy is considered to be poor practice today (Anon, 2013). Even more frequent off-site calibration intervals (every 90 or 30 days) still pose risks.

In the subsequent discussion, note that there are no agreed international definitions for the following terms, so they may vary between locations, states or countries.

The different types of calibration can be broadly classified as detailed below.

*Zero calibration* or self-test (usually on start-up) means using ambient air to check that the instrument is measuring 20.9 per cent O<sub>2</sub>, 300 or 350 ppm CO<sub>2</sub> and nil other gases. It is also possible to use a special calibration gas often called 'zero air' (air from which the carbon dioxide has been removed, often using a simple disposable filter) to zero calibrate for CO<sub>2</sub>.

(Functional) *bump testing* or *challenge testing* at its most basic level means using a bottle of compressed gas of known concentration(s) to ensure the sensors will alarm within a specified time when exposed to a concentration of gas above (or below, for O<sub>2</sub>) the alarm levels. In other words, it will respond to the 'challenge' of gas levels that should set it off. If the gas monitor is only being used to check for dangerous conditions and only needs to alarm when these occur, then this type of testing is possibly all that is required. Bump testing should be performed before the monitor is used each day. The compressed gas may also consist of a mixture of the particular gases that the monitor measures, which allows several challenge tests to occur using the one gas bottle. Bump testing usually checks both alarms are triggered, plus checks the audible and visible alarms on the monitor. Therefore, bump testing confirms that each gas is capable of reaching the sensors (protective membrane is not blocked, etc), that when the gas does reach the sensors that they respond, the response time (time-to-alarm) after gas is applied is within normal limits, and that the audible and visual alarms are activated and function properly. However, it does not check that the displayed (measured) values are actually correct (accurate).

In some contexts, bump testing may also (unfortunately) refer to checking the *accuracy* of the meter's sensors, often then called a 'calibration check'. This is important if the gas monitor is going to be used to record actual gas concentrations at given times or locations (eg for surveys or audits or for legal reasons). For example, the displayed LEL may be required to be within +0 per cent to -20 per cent of the true LEL and other gases to within ±10 per cent to 20 per cent of the known value (depending on the manufacturer's allowances). Whilst such a calibration check may check the accuracy of the monitor, it does not necessarily calibrate the monitor to the known values, even though this form of bump testing is sometimes referred to as 'calibration'. Modern bump testing

and calibration checks can be performed in seconds and often permanently record the instrument number and test results for every bump test. These records will be important if there is an incident involving a gas monitor. Where the monitor fails the calibration check, it must not be used until it has been recalibrated.

*Field calibration* or *span calibration* is similar in some ways to bump testing but the monitor is designed so that it can actually recalibrate itself to the known values from the calibration gas cylinder. Field calibration often uses a more sophisticated docking module that also charges the monitor and performs diagnostic checks and is therefore a more expensive system. In most cases, the monitor is only calibrated to a single known concentration of *each gas for which it has a sensor* (ie not across the full range of concentrations). Hence the term 'span calibration' as it recalibrates itself only to this upper value (as well as the nil concentration on start-up). With modern apparatus, if a bump test is performed and if it fails, the docking station will automatically initiate a span calibration.

*Laboratory calibration* or 'full calibration' means testing by an approved laboratory. This usually means the monitor is tested against more than one concentration of each gas.

### Calibration gases and cylinders

Calibration gases are certified compressed gas mixtures that are often also called span gases. Calibration gases are broadly classified into:

- Non-reactive gases, which are stable under most conditions. This includes mixtures of N<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>, CO, CH<sub>4</sub>, etc.
- Reactive gas mixtures in which at least one of the gases is reactive (Cl, H<sub>2</sub>S, SO<sub>2</sub>, HCl, NH<sub>3</sub>, etc).

Non-reactive gas mixtures have longer shelf lives and can be packaged in less expensive cylinders. Reactive gas mixtures are usually packaged in aluminium cylinders that are specially treated and passivated to reduce reaction with the reactive gas(es) inside.

Cylinders are usually between 34 and 58 L of compressed gas in size. This makes them quite small; for example, a 58 L compressed gas cylinder is about 1 L in size.

It is very important to not use calibration gas beyond its expiry date. The expiry date should be stamped on the cylinder.

Calibration gases are treated as dangerous goods in terms of transport and cannot be sent via air freight and are therefore intended as being disposable (non-returnable). In addition, a spare set of calibration gases should always be kept on-site as replacement can take some time because gas cylinders are made to order (usually only in a few selected countries in the world) and then there is the surface transport time involved.

Docking stations have a limited number of calibration gas input ports to which bottles of calibration gases can be connected. However, if a dock has four ports, it can still have ten or more gases being calibrated at that dock by using calibration gas cylinders that have been prepared as mixtures. Most calibration gas mixtures also have a 'balance gas' which is an inert carrier gas that fills up the rest of the bottle. Where a docking station has several gas inlet ports and one of these is connected to a mixed cylinder, it is important to check how much gas is required to calibrate that set of sensors. In most cases, the same amount of calibration gas is required whether there is only one target gas in the cylinder or many.



## Site versus off-site calibration

A system with site calibration means that additional instruments are not required to allow for the periods of time when instruments are off-site for calibration. Of course, it also means instruments are always reading accurately. Note that daily bump testing using calibration gases is now recommended by all manufacturers and also approving authorities in the USA and Australia, etc; ie it is no longer recommended that gas monitors simply be sent off for a calibration check every six to 12 months. Even if this was the case, then additional monitors are required to cover the operational needs when monitors are off-site.

## How a typical gas monitoring system operates in a mine

The main components are the gas monitors (with NiMH batteries), plug-in battery chargers and a single docking station (connected to cylinders of calibration gas) that does both bump testing and span calibrations of the monitors. At the end of each day, each monitor is dropped into its charger and is charged. Each morning before the monitor is used, it is turned on and then dropped into the docking station. It will automatically be bump tested. The docking station will give the monitor a pass or fail. If the monitor fails the bump test and/or at preset intervals (by the user), the bump test will be automatically followed by a span calibration (in the same device) which effectively means the monitor is recalibrated to the known gas concentrations from the cylinders.

The docking station should automatically download each day's data from the monitor and keep this on the docking station's own inbuilt memory or SD card for life. In addition, the docking station can be connected to a PC which has software that allows data to be downloaded into spreadsheets, or the various alarm levels of the monitors changed, etc.

## Storage of sensors, calibration gases, spare parts and battery packs

The shelf life issue of calibration gases has been previously discussed. Other spare parts and accessories for gas monitors should be stored at ambient temperatures of 0–30°C. Storage time should not exceed five years. Electrochemical sensors should not be stored for more than six months prior to being put into service. Oxygen sensors' lifetime commences from date of manufacture, so storage should be as short as possible on-site. When storing spare sensors make sure that the ambient atmosphere is free of corrosive media and sensor poisons. For spare NiMH battery packs storage time should be kept to less than one year. Before storing, the battery pack has to be charged completely. If gas monitors are stored for more than six months the battery pack should be removed.

## Suitable location for docking station

A clean (but not necessarily dedicated) room should be provided for the gas monitors and the docking station, calibration gas cylinders and personal computer. Most of the system can be left on a table although the docking station can be mounted via brackets to a wall. The entire system should be kept out of direct sunlight.

Always have the material safety data sheet for the various gases in their cylinders available, usually mounted on the wall.

## Case study

A 3.5 Mt/a gold mine needed to purchase a gas monitoring system. The following approach was used.

For an underground hard rock mine, the choice of gases for monitoring is discussed in Brake (2015). There are too many gases to fit on a single monitor, so two multigas monitors were initially designed at this operation, in this case referred to as an 'A' and a 'B' monitor. Whilst it would be desirable to have the 'A' monitor specifically set up to check for blasting gases, this is not always possible given the constraints on possible sensor combinations as discussed above. A compromise may be required. Furthermore, some users, such as diamond drillers, may only require a few gases so that at this mine there ended up being four differently configured monitors in use (A, B, C and D) to cover the needs of the various users in the most cost-effective manner.

## Example of calibration gases

For the monitors noted in Table 5, the following calibration gas mixtures were applicable. This allowed four different configurations of monitors (A, B, C and D) measuring nine gases between them to use a single four-port docking station.

Table 6 shows a selection of calibration gas mixtures.

## Selection criteria for gas monitors

The selection criteria used to evaluate the hand-held gas monitors at this operation were as follows:

1. Gases on A monitor compared to preferred combination.
2. Gases on B monitor compared to preferred combination.
3. Business of manufacturer.
4. Head office for technical matters.
5. Years of operation.
6. Years this model of detector in service.
7. Years spare parts will be available.
8. How often they need to be calibrated off-site (ie in a laboratory recommended by the supplier)? Where can this be done? How long will it take for turnaround (including transport) and the cost? Note that off-site calibration should be staggered to reduce the number of instruments off-site at any time.
9. Can calibration be done in the field and if so, what equipment, training and cost is involved? How long does a bump test or field calibration take (seconds) and how long if several instruments need to be bump tested and calibrated immediately after one another? Note: If instruments can be field-calibrated, then fewer instruments may be needed as spares are not required for when instruments are off-site being calibrated.
10. Time required for bump testing: both for each single instrument and all instruments that need to use this dock each day.
11. Time required for span calibration: both for each single instrument and all instruments that need to use this dock.
12. Does calibration reduce the life of the sensors?
13. How many bump tests and span calibrations can be done on each bottle of calibration gas?
14. Recommended spare parts holdings for the specific location of the mine.
15. Any special issues regarding dangerous goods transport, or special storage or location instructions on-site (eg air conditioning, refrigeration, etc)?
16. What is the life of the sensors and can they be replaced in the field?
17. Are the sensors interchangeable (ie can be hot-swapped out)? This is important otherwise when the sensor gets to end of its life, the monitor must be returned to have

TABLE 5

Typical gas monitor sensor configuration for hard rock mine (GfG (proprietary brand) monitor were selected in this case study).

	Gas	Type of sensor	TWA	STEL	Sensor range	Resolution	Tolerance band <sup>b</sup>	t <sub>50</sub> /t <sub>90</sub> (seconds) <sup>c</sup>	Low/high alarm set points	Life of sensor (years)	Cost of sensor (R)	Calibration gas concentrate <sup>e</sup>
A	CO	'Dual EC'	30 ppm	90 ppm <sup>a</sup>	0–500 ppm	0.1 ppm	3 ppm	15/45	30/60 ppm	3	4746	100 ppm
	H <sub>2</sub> S		10 ppm	15 ppm	0–100 ppm	0.5 ppm	1.5 ppm	15/45	10/20 ppm	Incl in CO	Incl in CO	25 ppm
	SO <sub>2</sub>	EC	2 ppm	5 ppm	0–10 ppm	0.1 ppm	0.2 ppm	30/75	2/4 ppm	3	4038	10 ppm
	NO <sub>2</sub>	EC	3 ppm	5 ppm	0–30 ppm	0.2 ppm	0.6 ppm	10/30	5/10 ppm	3	4038	20 ppm
B	LEL/CH <sub>4</sub>	CC			0–100% LEL	0.5% LEL or 0.02% CH <sub>4</sub> (selectable)	2.5% of LEL or 0.14% CH <sub>4</sub>	10/25	20/40/60 % LEL <sup>d</sup>	3	3169	2.5%
	CO <sub>2</sub>	IR	0.5%	3%	0–5%	0.01 or 0.05% (selectable)		20/60	0.5/ 3%	6	9476	2%
	O <sub>2</sub>	EC	>18%	none	0–25%	0.1%	0.3% vol	5/20	19/17%	2	2880	18%
	NO	EC	25 ppm	75 ppm <sup>a</sup>	0–100 ppm	1 ppm	3 ppm	15/40	25/50 ppm	2 to 3	4038	50 ppm
	NH <sub>3</sub>	EC	25 ppm	35 ppm	0–200 ppm	1 ppm	3 ppm	20/60	50/100 ppm	2 to 3	5679	100 ppm

- No short-term exposure limit (STEL). This value based on general recommendation of STEL at three times the time weighted average (TWA). Where a substance has no STEL or ceiling, the American Conference of Government Industrial Hygienists (ACGIH, 2015) provides this guidance: 'Excursions in worker exposure levels may exceed three times the TLV-TWA for no more than a total of 30 minutes during a workday, and under no circumstances should they exceed five times the TLV-TWA provided that the TLV-TWA is not exceeded'. Alternately, the National Occupational Health and Safety Commission (NOHSC, 2013) also provides a guidance note on CO.
- See text for discussion of tolerance band and accuracy. Do not confuse T-band with accuracy. Accuracy of a sensor varies with temperature, barometric pressure and time.
- Note: these t<sub>50</sub> and t<sub>90</sub> values are based on the sensors installed in the monitor. Other manufacturers quote these values based on 'raw' sensors not installed in their monitors and are therefore not comparable.
- Lower exposure limit (LEL) has three alarm settings; all others have only two.
- Note that for bump testing, the calibration gas concentration must be greater than the *low* alarm set point (A1) but less than the upper measurement range of the sensor. For example, for CO, the A1 limit is 30 ppm and the upper range of the CO sensor is 500 ppm, so the calibration gas must be between 30 ppm and 500 ppm. For NO, the A1 limit is 25 ppm and the sensor upper range is 100 ppm and the calibration gas is 50 ppm. A further indication is that the Canadian Standards Association C22.2 NO. 152-M1984(R2001), 'Combustible Gas Detection' Section 5.3 para (k) states 'Caution: before each day's usage sensitivity must be tested on a known concentration of \_\_\_\_\_ (specify gas) equivalent to 25–50% of full scale concentration. Accuracy must be within -0–+20% of actual'.

TABLE 6

Example of selection of calibration gas mixtures to allow nine gases to be tested by a single four-port dock with three different gas monitors.

Cylinder 1	58 L	Sulfur dioxide ppm 10, hydrogen sulfide ppm 25, carbon monoxide ppm 100, methane % 2.5 (50% LEL), oxygen % 18, nitrogen balance
Cylinder 2	58 L	Nitrogen dioxide ppm 20, carbon dioxide % 2, air balance
Cylinder 3	58 L	Nitric oxide ppm 50, nitrogen balance
Cylinder 4	58 L	Ammonia ppm 100, nitrogen balance

each sensor replaced when it goes off (and they all have different lives).

- Will the instrument tell the operator when the sensor needs to be replaced?
- Whether the detector is active [sample draw] (pumps air through its sensors) or passive [diffusion] (relies on the air diffusing through the sensors). Active sensors may come with a sampling pump and hose which allows measurement in tanks or pipes or behind walls where the operator and monitor may not be able to travel (eg in a mine, this could be a sealed-off area).
- Whether the monitor can do continuous logging or event logging (recording when the alarms went off and times).
- Whether the warning and danger alarm levels can be set by the user.
- The response times of the sensors, eg the rise time to 90 per cent of final value (t<sub>90</sub>), rise time to 50 per cent of final value (t<sub>50</sub>), and the recovery (or 'fall') time to ten per cent of original value. Note that these will vary with many factors including the age of the sensor and so data provided may only be true with new sensors. The issue of response times is mainly of concern with diffusion type monitors.
- Resistance of sensors to poisoning and cross-sensitivity of sensors (ie specificity).
- Standalone ability of docking station (without laptop).
- Standalone ability of docking station (without internet).
- Weight.
- Size.
- Colour screen.
- Size of screen (diagonal).
- Dust and waterproofness.
- Intrinsic safety (in explosive zones). It is pointless having an 'LEL meter' if it cannot be used in explosive atmospheres.
- Robustness and reliability.
- Drop height.
- Operating temperature, humidity.
- Operating pressures and elevations.
- Ability to handle changes in temperature and condensation.
- Instantaneous alarm levels.
- Time-weighted alarm levels (dosimeter alarms).

39. Battery-low alarm.
40. Alarm notifications (visible, audible and vibrating).
41. Warranty.
42. Servicing.
43. Spare parts.
44. Ease of use underground (backlighting, large digits, high sound level alarms, etc).
45. Ability to mount/attach monitor to belt, shirt collar, pocket, etc.
46. Language support.
47. On-site training (or off-site training).
48. Comprehensiveness of the operating manuals.
49. Ability to update firmware from site.
50. Hand-held (and if so, one hand or two hands)?
51. Number of buttons to operate.
52. Size of buttons.
53. Type of battery and battery life/memory effects. The ability to use rechargeable batteries as well as disposable can be an advantage if the gas monitor battery is flat but suddenly needs to be used for test purposes.
54. Operating time between charging.
55. Battery recharge time (from fully discharged).
56. Initial purchase cost for system including software, single set of all calibration gases, rechargeable battery packs, probes including training.
57. Annualised calibration gas cost if all instruments (four total) bump tested 300 days per year and calibrated 12 times per year.
58. Sensor cost annualised.
59. Battery pack cost annualised.

## CONCLUSIONS

The use of electronic gas monitors and monitoring systems is now considered to be good practice, and in some jurisdictions, mandatory for routine and non-routine gas monitoring. On-site calibration of instruments provides a much lower product life cycle cost than the traditional system of sending monitors off-site for laboratory calibration.

There are now many such gas monitoring systems available for the mine ventilation engineer and other users

underground. However, complete systems are expensive and a good understanding of the sensor and calibration options is essential to avoid disappointment or even unsatisfactory choices being made. The mine ventilation engineer cannot rely on the suppliers of the gas monitors to establish the needs in his operation as underground mines are usually only a small and specialised segment of the market. Assessing different offers from suppliers can be confusing if the important issues are not understood.

## ENDORSEMENTS

Nothing in this paper should be taken as a recommendation by the author of any particular supplier of gas monitors. GfG gas monitoring equipment was used in this case study.

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APPENDIX 1

**TABLE A1**  
 Comparison of the three main sensor types used in hand-held gas monitors for underground mines  
 (text summarised from Anon, 2014a, and Schlosser, Robertson and Kaplan, undated).

Catalytic combustion		Electrochemical		Infrared	
<p>In a catalytic sensor both a reference bead and an active bead are held at a constant temperature. The chemical oxidation of a combustible gas on the active bead creates a temperature increase. This temperature increase changes the resistance of the wire, which is usually made of platinum. This change in resistance is related to the gas concentration.</p>		<p>Electrochemical sensors contain two active electrodes in a casing: the working electrode (anode) and the counter electrode (cathode). The top of the casing has a membrane through which the gas sample permeates. Chemical changes take place at the electrodes and the charge is conducted through the sample phase or gel within the casing. The electrode reactions and the charge transport indicate whether or not a toxic gas is present as well as the relative amount present.</p>		<p>Infrared sensors measure two wavelengths: a reference and a sample wavelength. The ratio of the sample wavelength energy to the reference wavelength energy indicates the gas concentration. If the gas being monitored or detected is present between the mirror and the main detector, the sample wavelength will be absorbed and the reference wavelength will not be absorbed. This difference in radiation indicates the gas concentration.</p>	
Advantages compared to infrared (IR)	Disadvantages compared to IR	Advantages	Disadvantages	Advantages compared to catalytic	Disadvantages compared to catalytic
<ul style="list-style-type: none"> <li>• Robust.</li> <li>• Simple to operate.</li> <li>• Easy to install, calibrate and use.</li> <li>• Long life with a low replacement cost.</li> <li>• Proven technology with exceptional reliability and predictability.</li> <li>• Easily calibrated individually to gases such as hydrogen which cannot be detected using infrared absorption.</li> <li>• Can perform more reliably in dusty and dirty atmospheres as they are not as sensitive as optics to the build-up of industrial contaminants.</li> <li>• Can perform more reliably in high temperature applications.</li> <li>• Are less sensitive to humidity and condensation.</li> <li>• Not as significantly affected by changes in pressure.</li> <li>• Can detect most combustible hydrocarbons.</li> </ul>	<ul style="list-style-type: none"> <li>• Catalysts can become poisoned or inactive due to contamination (chlorinated and silicone compounds, prolonged exposure to H<sub>2</sub>S and other sulfur and/or corrosive compounds).</li> <li>• The only means of identifying detector sensitivity loss is by checking with the appropriate gas on a routine basis and recalibrating as required.</li> <li>• Requires oxygen for detection.</li> <li>• Prolonged exposure to high concentrations of combustible gas may degrade sensor performance.</li> <li>• If flooded with a very high gas concentration, may show erroneously low or no response, and sensor may be damaged or rendered inoperable.</li> </ul>	<ul style="list-style-type: none"> <li>• Can be specific to a particular gas.</li> <li>• Accurate.</li> <li>• Do not get easily poisoned.</li> <li>• Monitor at ppm levels.</li> </ul>	<ul style="list-style-type: none"> <li>• Narrow temperature range.</li> <li>• Short shelf life.</li> <li>• Subject to interfering gases (eg hydrogen).</li> <li>• Sensor lifetime will be shortened in very dry, hot areas.</li> </ul>	<ul style="list-style-type: none"> <li>• Immunity to contamination and poisoning.</li> <li>• Consumables (source and detector) tend to outlast catalytic sensors.</li> <li>• Can be calibrated less often than a catalytic detector.</li> <li>• Ability to operate in the absence of oxygen or in enriched oxygen.</li> <li>• Ability to operate in continuous presence of gas.</li> <li>• Can perform more reliably in varying flow conditions.</li> <li>• Even when flooded with gas, will continue to show high reading and sensor will not be damaged.</li> <li>• Able to detect at levels above 100 per cent lower explosive limit.</li> </ul>	<ul style="list-style-type: none"> <li>• The initial higher cost per point. IR detectors typically are more expensive than catalytic detectors at initial purchase.</li> <li>• Higher spare parts cost.</li> <li>• Gases that do not absorb IR energy (such as hydrogen) are not detectable.</li> <li>• High humidity, dusty and/or corrosive field environments can increase IR detector maintenance costs.</li> <li>• Temperature range for detector use is limited compared to catalytic detectors.</li> <li>• May not perform well where multiple gases are present.</li> </ul>