Evaluation of Person-Wearable Methane Monitors

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ABSTRACT

Regular monitoring for methane gas is required near working faces in gassy underground mines where the potential for methane ignitions is greatest. However, high concentrations of methane can also accumulate outby the face where methane levels are monitored less frequently. Wearing a personal methane monitor equipped with an alarm could protect persons working in these outby areas from injury or death due to methane ignitions.

The National Institute for Occupational Safety and Health (NIOSH) has conducted studies to evaluate methanometers that could be used as person-wearable monitors.

For the present study, seven different person-wearable monitors that are not currently approved for underground use were evaluated. This paper describes test procedures used to evaluate performance of methane monitors that could be used underground for continuous personal monitoring of methane. The information in this report provides data that allows the reader to make side-by side comparisons of these instruments.

BACKGROUND

Continuous methane monitoring on a mining machine is required near face areas of gassy underground mines (30 CFR § 75.323(b)). Except for areas where atmospheric monitoring systems (AMS) are located, methane concentrations are not monitored on a daily basis in outby areas. In the United States methane ignitions continue to occur in work areas that are outby the active work faces (McKinney, 2001). A person-wearable methane monitor that continuously monitors methane levels would give warnings when methane levels were too high at any work location.

Previously NIOSH evaluated a person-wearable methane monitor, used in South African mines, that combines the cap lamp and methanometer in a single unit (Chilton, Taylor and Timko, 2003). The instrument's design made it easy to wear, but difficult to calibrate because it did not have a visual readout. Personal wearable monitors that could be used to detect methane in these outby areas are not used in US underground mines. Seven different person-wearable methane monitors, currently not used underground, were selected for testing because:

- they are small enough to be worn by an underground worker;
- they all have a digital readout to indicate methane concentration; and
- they each have visual, audible, and vibratory alarms to alert workers when the detected methane levels exceed preset limits.

GENERAL DESCRIPTION

The seven methanometers (identified in the text as instruments A through G) that were evaluated are shown in Figure 1. The weight and size of the instruments varied as shown in Table 1. Each instrument has a clip that allows it to be attached to a worker's clothing or belt.

All of the methanometers use catalytic heat of combustion sensors. Combustible gas from the surrounding environment reaches the sensor element by diffusion. Filters remove any airborne dust or water mist before it reaches the sensor element. Although all methane monitors used in US mines display methane concentrations as a per cent by volume, the instruments tested display concentration as per cent of the lower explosive limit (LEL). All of the instruments measure from zero to 100 per cent LEL methane which is equivalent to zero to five per cent by volume methane.

FIG 1 - Methanometers used in NIOSH study.

TABLE 1

Methanometer size and weight.

Instrument	Height (mm)	Width (mm)	Depth (mm)	Weight (g)
A	110	52	27	170
B	95	50	38	131
C	152	44	25	197
D	130	60	30	210
E	109	62	35	243
F	122	62	34	250
G	105	35	20	100

INSTRUMENT EVALUATIONS

Methanometer performance was evaluated based on the following parameters:

- run time,
- measurement drift,
- response time, and
- alarm characteristics (visual, audible, vibratory).

Instrument run time

New nickel metal hydride (NiMH), nickel cadmium (NiCad), or lithium ion (Li-ion) batteries (Table 2) supplied by the instrument manufacturer are used to power the instruments.

1. NIOSH/Pittsburgh Reseach, Respiratory Hazard Control Branch, 626 Cochrans Mill Road, Pittsburgh PA 15236, USA.
2. NIOSH/Pittsburgh Reseach, Hearing Loss Prevention Branch, 626 Cochrans Mill Road, Pittsburgh PA 15236, USA.

TABLE 2
Methanometer run time comparisons.

Instrument	Battery type	Manufacturer stated run time (hr)	Average measured run time (hr)
A	NiMH	6	2.67
B	Li-ion	12-14	12.17
C	NiCad	12	10
D	NiMH	12	11.50
E	Li-ion	18	20
F	NiMH	11	12
G	NiCad	8	12.5

A methanometer's run time is the total amount of time it will monitor gas concentrations before its battery voltage drops below a minimum level. Each of the instruments has a warning signal to indicate low battery voltage.

To measure run time the batteries were first charged according to the manufacturers' instructions. The instruments were turned on at the beginning of an eight-hour workday. All testing was conducted in fresh air. Any instrument that was still operating normally after eight hours was turned off. Without being recharged, it was turned on at the beginning of the next workday and run times continued to be measured. Run times were measured twice for each instrument and the results averaged. The manufacturers' stated run times and average measured run times are listed in Table 2.

Measurement drift

A methanometer is calibrated by exposing the instrument to zero gas and to an air gas mixture containing a known methane concentration. The instrument output is adjusted until the visual readout displays the concentration of the applied gases. Over time some measurement drift is normal, but the readings should remain within specified tolerances.

After the instruments were calibrated, drift tests were conducted to determine how much methane readings varied with time when the instrument was exposed to known gas concentrations. No further adjustments were made to instrument calibration after starting the tests; however, instrument G automatically checked the zero reading each time the instrument was turned on by way of a fresh air start-up mode.

Drift tests were conducted by placing all seven instruments in a 360 × 360 × 360 mm enclosed chamber. Figure 2 shows the chamber containing one instrument. The methanometers' visual readouts could be seen through the chamber's Plexiglas® top. Twice each day, morning and afternoon, a Hamilton 1500 ml syringe (reference to specific products does not imply endorsement by NIOSH) was used to inject 1300 ml of 99 per cent methane gas into the box. Two small fans at the bottom of the chamber completely mixed the gas and air in about four seconds. As the gas was injected, leakage of the methane-air mixture occurred through small openings in the box. The resulting methane concentration in the box was approximately 50 per cent LEL (2.5 per cent by volume). One minute after the gas was injected the instrument readings were recorded.

An Industrial Scientific MDU 420 infrared portable methanometer was also placed in the chamber to be used as a reference instrument. The accuracy of this instrument was checked by performing a calibration prior to each test. The readings from the reference instrument during calibration and in the box were used to normalise concentrations in the chamber to 50 per cent LEL (2.5 per cent by volume). The drift tests were repeated on 12 consecutive working shifts giving a total of 24 measurements. Figure 3 shows the normalised first-minute LEL per cent concentrations for each measurement taken.

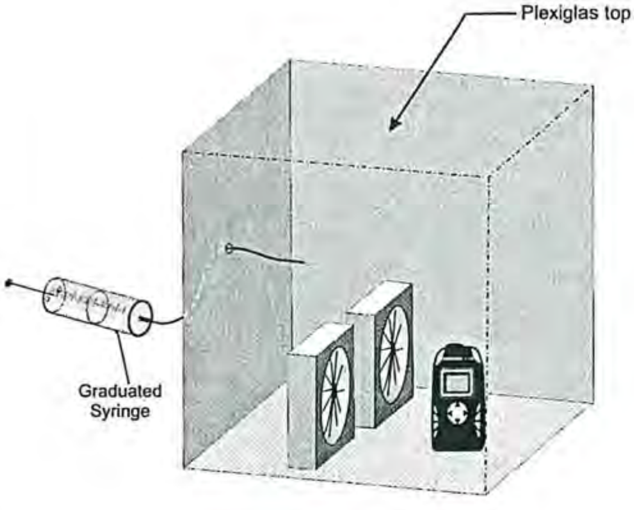

FIG 2 - Enclosed chamber used for measurement drift tests.

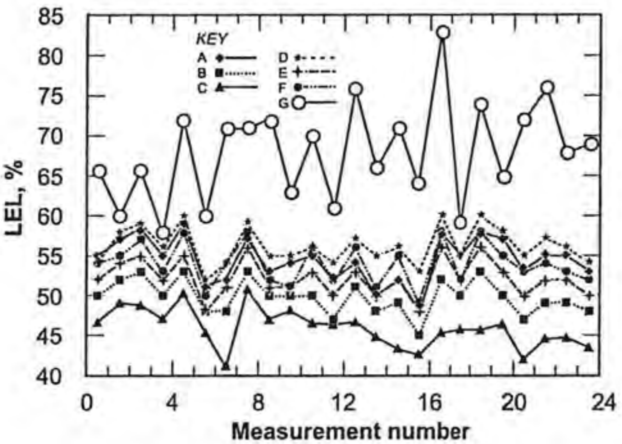

FIG 3 - Methanometer drift test results.

Instrument response time

Instrument response time for a methanometer is defined as the time interval for the methanometer output to change from a steady state or zero reading in pure air to a given percent value (90 per cent of the full-scale value in this case) of the final steady state reading upon application of a known gas concentration. Response times were measured for each of the seven methanometers using a procedure developed by NIOSH (Taylor, Chilton and Zimmer, 2004).

The instruments were tested individually in the enclosed chamber described earlier. The Hamilton syringe was used to inject 1300 ml of 99 per cent methane. After the gas was injected, the concentrations were recorded from the instruments' visual readout every five seconds for one minute. After one minute, the final or full-scale reading was recorded. Measurements were taken twice for each instrument and the results averaged. Response time curves (Figure 4) were drawn by plotting the percent of full scale readings versus elapsed times for that reading. The dashed line on Figure 4 intersects each curve at the 90 per cent response time.

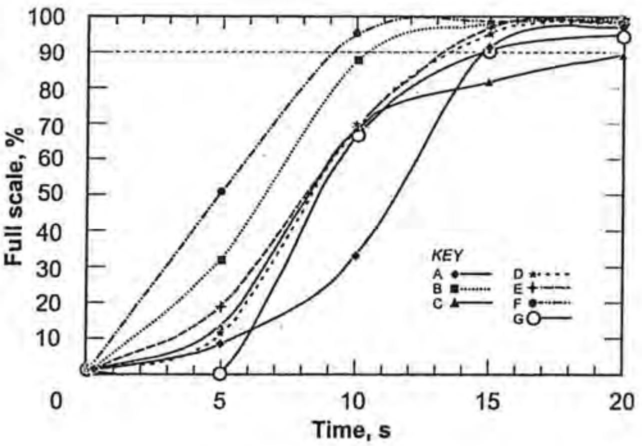

FIG 4 - Response time plots.

Instrument alarms

All seven methanometers tested have visual, audible, and vibratory alarms that produce signals to warn the user when preset gas concentrations are exceeded. All of the instruments, except instrument A, have two separate alarms that can be set independently for 'low' and 'high' gas concentrations. The low and high alarms were turned on by applying either 20 or 40 per cent LEL (one or two per cent by volume) methane gas, respectively, to the sensor head. Each type of alarm (visual, audible, and vibratory) was evaluated separately for each instrument.

Visual alarms

The methanometers have one or more red light emitting diodes (LEDs) that are located on the top, side, or front of the instruments (Table 3). Each instrument has a different temporal light pulse pattern.

TABLE 3

Number and location of LEDs.

Instrument	Number	Location
A	1	Top
B	2	Top
C	1	Top
D	2	Top
E	1	Front
F	2	Top
G	3, 1	Side, Top

The alarm light intensity and temporal pattern were measured by placing the alarm lights approximately 1 cm from a photodiode. A constant voltage was supplied to the photodiode. The current from the photodiode changes with the amount of light. This current is proportional to the voltage drop across a 50 ohm resistor that was in series with the photodiode. The voltages were recorded by a computer-based data acquisition system (100 Hz sample rate). The magnitudes of the measured voltages (signal mv) were proportional to the light intensities as shown in Figure 5. The light pulse rates and cycle times (on and off) are shown in Figures 6 to 8.

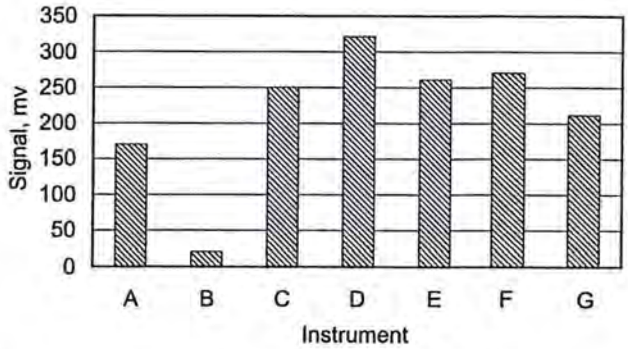

FIG 5 - Light signals 1 cm from photodiode.

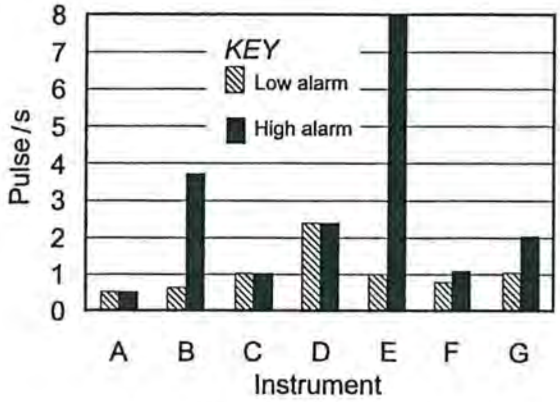

FIG 6 - Methane alarm light pulses.

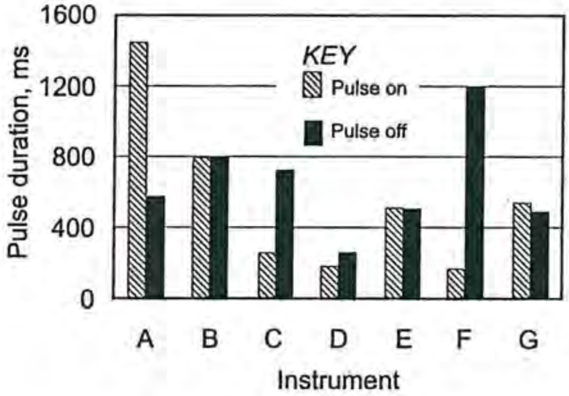

FIG 7 - Low methane alarm pulse duration.

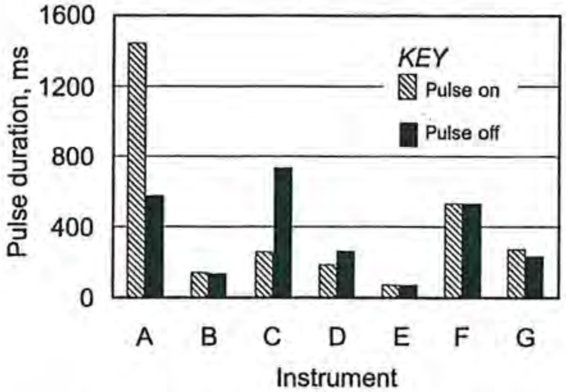

FIG 8 - High methane alarm pulse duration.

Audible and vibratory alarms

An audible alarm is produced by a speaker located in either the front or top of the methanometer (Table 4). A vibratory alarm is produced by a motor that rotates an eccentrically weighted shaft. The vibratory alarm was located inside methanometers A, B, E, F, and G. Instruments C and D have external vibrators that are controlled by signals from the methanometers.

TABLE 4
Speaker locations.

Methanometer	Speaker location
A	Front
B	Front
C	Top
D	Top
E	Front
F	Front and top

Sound and vibration measurements were made inside the NIOSH anechoic chamber. During each test the methanometer was placed on two small pieces of soft foam with the visual readout facing up. Supporting the methanometer in this manner in the anechoic chamber simulates free boundary conditions and has little impact on the measured vibration.

Sound level and temporal patterns for each alarm's audible signal were measured using two Type-1 ICP-powered microphones. The microphones were positioned 0.3 metres from the top and 0.3 metres from the front centre of the methanometer (Figure 9). The recorded data was used to determine the sound levels and temporal patterns for each alarm's audible signal.

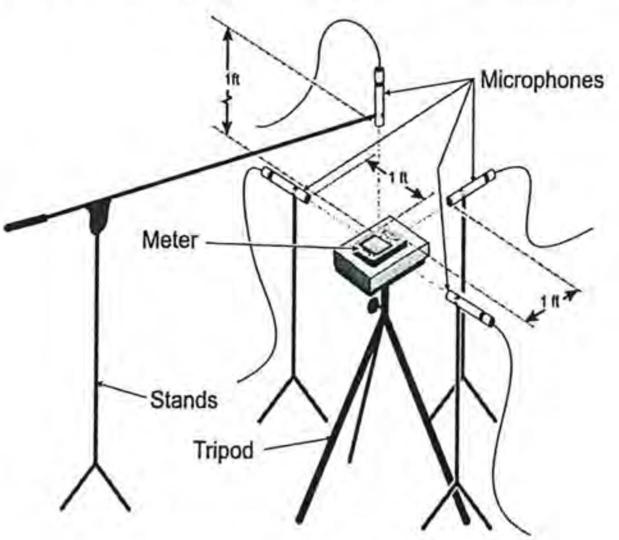

FIG 9 - Microphone orientation.

A lightweight triaxial accelerometer was used to measure vibration and mounted on the case of the methanometer or the external vibrator. The accelerometer axes were aligned with the axes of the instrument cases (Figure 10) or the external vibrators (Figure 11).

A 16-bit resolution LMS Pimento portable data acquisition system was used to simultaneously record sound and vibratory acceleration data. Sample rates for the sound and vibration data were 50 000 and 5000 samples per second, respectively. Each recording was approximately ten seconds in length. The recorded

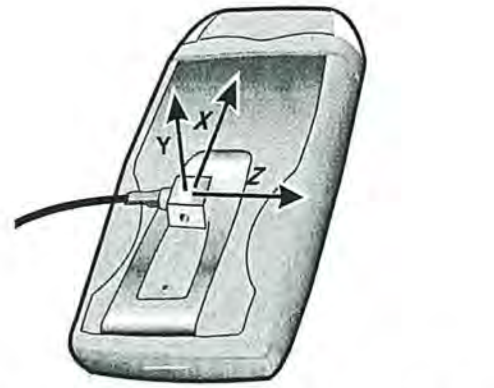

FIG 10 - Accelerometer placement on methanometer case (instrument D).

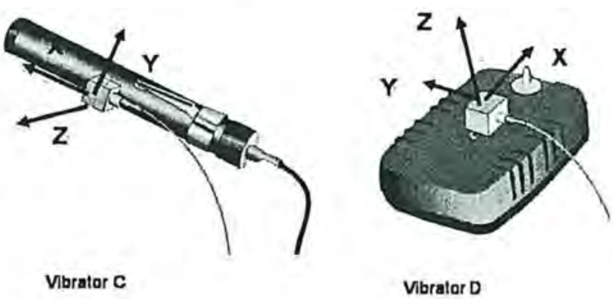

FIG 11 - Accelerometer mounted on external vibrators C and D.

sound pressures were post-processed to determine the maximum A-weighted sound levels, the frequency content, and temporal characteristics of each alarm signal.

Sound level

The maximum A-weighted sound levels with fast response measured at the top and front microphone locations for the entire frequency distribution are shown in Table 5.

TABLE 5
Maximum A-weighted sound levels.

Instrument	Alarms	Maximum A-weighted sound level with fast response (dB re 20 µPa)	
		Top	Front
A	Low/high	72	78
B	Low	83	88
B	High	82	87
C	Low	74	72
C	High	75	73
D	Low	86	85
D	High	85	85
E	Low	74	86
E	High	72	84
F	Low	88	84
F	High	88	85
G	Low	82	79
G	High	81	78

Sound frequency

The 1/3-octave band sound pressure level (SPL) spectra were calculated for each recording using a fast time constant. The spectra at the times corresponding to the maximum A-weighted sound level (Table 5) were examined for top and front microphone locations. The 1/3-octave bands yielding the highest and second highest sound pressure levels were determined. The sound pressure levels and the associated 1/3-octave band centre frequencies are given in Table 6 for the top measurement location. Similar results were obtained for the front sampling location.

TABLE 6

Highest and second highest 1/3-octave band sound pressure levels at top microphone.

Instrument	Alarm	Highest 1/3-octave band SPL at frequency	Second highest 1/3-octave band SPL at frequency
A	High/Low	70 dB at 2500 Hz	63 at 3150 Hz
B	Low	82 dB at 5000 Hz	72 at 4000 Hz
B	High	80 dB at 5000 Hz	76 at 4000 Hz
C	Low	69 dB at 2000 Hz	69 at 4000 Hz
C	High	71 dB at 2000 Hz	70 at 4000 Hz
D	Low	83 dB at 4000 Hz	77 at 2000 Hz
D	High	83 dB at 4000 Hz	77 at 2000 Hz
E	Low	71 dB at 5000 Hz	67 at 2500 Hz
E	High	70 dB at 5000 Hz	65 at 2500 Hz
F	Low	84 dB at 2000 Hz	83 at 4000 Hz
F	High	86 dB at 2000 Hz	80 at 4000 Hz
G	Low	79 dB at 4000 Hz	76 at 2000 Hz
G	High	78 dB at 4000 Hz	74 at 2000 Hz

Sound temporal patterns

Temporal patterns of the audible alarm refer to both the rate at which the audible signal repeats itself and the changes in sound frequency/pitch. Dominant and fundamental frequency tones for each alarm signal were determined using narrowband frequency analysis (Table 7). For instruments A, C, D, E, F, and G, the repeating signal consisted of alternating pulses with fixed frequency content, whereas for instrument B the signal consisted of alternating pulses that began at one frequency and swept to a higher frequency. Table 7 also shows the cycle time (seconds needed for the signal pattern to repeat one time).

Vibration

The measured accelerations were filtered and double-integrated to yield vibratory displacement in micrometers. The RMS displacement was calculated for each axis. The 1/3-octave band vibratory displacements were calculated for the steady state vibration signal in the direction of the axis having the highest displacement. The steady state displacement and corresponding 1/3-octave band centre frequencies are shown in Table 8.

DISCUSSION

General description

The seven methanometers tested are all small enough to be worn by a miner, either attached to the belt or the jacket. Sampling location on the miner is an important factor that can affect the accuracy of the methane readings and the ability of the user to react to instrument warnings of high methane concentrations. The instrument should be located on the miner so that air can pass freely over the sensor head and the user can recognise one or more of the alarm signals.

Instrument run time

Measured run times varied from less than three hours to 20 hours. Four of the instruments had run times that exceeded the manufacturers' stated run times. The battery charge for instrument E was not depleted until the third day. Although instrument A had an initial run time of 2.67 hours, after recharging several times, the instrument ran for five hours. To provide full-shift methane monitoring, instrument run times should be ten hours or longer. Aging of the instruments will reduce run time as will operation of the alarms during a shift. The user must monitor battery condition to ensure that power to the methanometer is adequate.

TABLE 7

Temporal patterns determined by narrowband frequency analysis.

Instrument	Alarm type	Tone (Hz) dominant/ fundamental	Pulse (P)						P/sec	Notes
			On	Off	On	Off	On	Off		
A	low/ high	2754/2754	1.44	0.56	1.44	0.56	---	---	0.5	---
B	low	4229-4986/4229-4986	0.52	0.25	---	---	---	---	1.3	sweep
B	high	4087-4978/4087-4978	0.14	---	---	---	---	---	7.1	sweep
C	low	4275/2137	0.06	0.06	0.07	0.82	---	---	1.0	---
C	high	4275/2137	0.06	0.06	0.07	.003	0.07	0.75	1.0	---
D	low	3970/1985	0.44	0.41	---	---	---	---	1.2	---
D	high	2149/3970	0.42	0.42	---	---	---	---	2.3	---
E	low	4904/2452	0.50	0.50	---	---	---	---	1.0	---
E	high	4904/2452	0.65	0.63	---	---	---	---	7.8	---
F	low	1919/1919	0.32	1.00	---	---	---	---	0.8	---
F	high	1919/2108	0.53	0.53	---	---	---	---	0.9	---
G	low	4097/2049	0.25	0.75	---	---	---	---	1.0	---
G	high	4097/2049	0.13	0.40	0.10	0.37	---	---	2.0	---

TABLE 8

RMS displacement.

Instrument	Alarm	Axis	Displacement (μm)	Frequency (Hz)
A	Low/High	Z	5.43	160
B	Low	Y	9.10	125
B	High	Y	9.18	125
C	Low	Z	21.8	100
C	High	Z	22.2	100
D	Low/High	Z	7.61	125
E	Low	Y	5.25	125
E	High	Y	4.34	100
F	Low	Y	5.58	125
F	High	Y	5.60	125
G	Low	X	18.6	100
G	High	X	10.5	80

Measurement drift

Average readings for six of the seven methanometers were equal to or greater than the 50 per cent LEL (2.5 per cent by volume) concentration in the test chamber. The instrument drift test data were analysed to determine average values and standard deviations (Table 9) for the 22 measurements made during the drift tests (Figure 3). A ten per cent deviation is acceptable for the accuracy of methanometers approved for use in underground mines when measuring 50 per cent LEL (2.5 per cent by volume) methane gas. (30 CFR § 22.7 (d)(2)). Five of the seven instruments fell within the ten per cent criteria. The drift as indicated by the standard deviation about the individual means is less than three per cent for six of the seven instruments.

TABLE 9

Instrument drift calculations.

Instrument	Mean	Standard deviation	Per cent difference from 50
A	54.3	2.8	8.5
B	49.8	2.2	0.4
C	45.9	2.5	8.1
D	56.2	2.3	12.3
E	52.2	2.4	4.3
F	54.0	2.7	8.0
G	68.0	6.3	36.1

When using methanometers, calibration to correct for instrument drift should be performed as needed, but at intervals not to exceed 31 days (30 CFR § 75.342 (a)(4)). The amount of instrument drift would be expected to increase with instrument age and exposure to dust and water.

Response time measurements

Currently there are no response time criteria for methanometers used in mines. However, the faster the response time the more quickly the instrument will provide a warning alarm signal. The measured response time for 90 per cent of the full-scale readings, T_{90} (Table 10), were determined from the response curves. Response times for the person-wearable methanometers varied from eight to 20 seconds. These times were faster than response times measured for mining-machine-mounted methane monitors equipped with filters for removing airborne water and dust (Taylor, Chilton and Zimmer, 2004).

TABLE 10

Ninety per cent response times.

Measured response times	
Instrument	T_{90} (sec)
A	15
B	10
C	20
D	13
E	13
F	8
G	15

Visual alarms

The effectiveness of a visual alarm depends on the location, intensity, and the temporal flashing pattern of the light(s). For a visual alarm to be recognised by the user, the instrument must be worn so that the light or lights are in line of sight.

In general the more intense the light the more likely it will be recognised by the user. In a dark underground environment the temporal pattern may be however, as important as the intensity. Light pulse rate and pulse duration are two key factors that affect the recognition of visual alarm signals. As shown in Figures 7 and 8, instruments B, E, F, and G all have pulse rates that differ at low and high alarms; instrument E has the largest difference in pulse rates.

Audible alarms

Sound level

In general a signal sound will be clearly audible if the A-weighted sound level of the signal exceeds the level of the ambient noise by 15 dB or more (ISO Standard 7731).

The maximum A-weighted sound levels (Table 6) ranged from 72 to 88 dB for the top microphone location. Since ambient A-weighted sound levels near operating machinery in underground mines are generally in excess of 85 dB, the audible alarms would probably not be heard by miners working in face areas. In areas outby the face, where machinery is not however operating, the audible alarms would probably be heard by the person wearing the instrument.

Signal frequency

An alarm signal should be based on frequencies in the 300 Hz to 3 kHz frequency range, and the signal should have sufficient sound energy below 1500 Hz to be heard by workers with hearing loss and workers wearing hearing protection (ISO Standard 7731). The more the frequency at which the alarm signal generates its highest sound level differs from the frequency where the ambient sound level is highest, the easier it will be for workers to hear the warning signal.

All of the instruments except B produced audible alarms having frequencies in either the highest or second highest 1/3-octave bands that were in the 300 Hz to 3 kHz range, but none generated sound energy below 1500 Hz. Instrument B generated a pulse that swept from a low to high frequency, while the other six instruments generated warning signals with fixed frequency content.

Temporal characteristics

Recognition of an audible alarm also depends on the pulse rate of the signal (Table 7). Six of the instruments (A, C, D, E, F, and G) had pulse frequencies in the range of the 0.2 Hz to 5 Hz (period of 0.2 to five seconds), which is recommended range for audible alarms (ISO Standard 7731).

Vibratory alarm

The skin is most sensitive to vibration frequencies from 200 Hz to 300 Hz (Salvendy, 1987). Recognition of the vibratory alarms also depends on displacement. Table 8 shows that whereas the vibratory frequencies ranged to 80 Hz to 160 Hz, for these tests, displacements ranged from approximately 5.4 to 22.2 μm. External vibrators can be placed closer to the user's skin while keeping the methanometer on outer clothing.

CONCLUSIONS

This study investigated seven different types of person-wearable methane monitors. Factors of instrument performance and alarm function that would be important in protecting a worker from exposure to high methane concentrations in an underground mine were examined.

Six of the methanometers had run times that were ten hours or greater. The drift for instrument G was more than three times the accepted range for accuracy (ten per cent), and the standard deviation was three times greater than the other instruments.

The 90 per cent response times for these methanometers were eight to 20 seconds.

Six of the methanometers tested have separate signals for high and low alarms. The first or low alarm was set at 20 per cent LEL (one per cent by volume). The second or high alarm was set at 40 per cent LEL (two per cent by volume). These levels correspond to warning and danger levels prescribed for machine monitoring systems (30 CFR § 27.22 (b)(2)). The methanometers are designed to alert the user of potential problems due to the accumulation of methane. The low alarm is a warning signal and the high alarm is a danger signal. Both require action on the part of the miner.

The monitors all have digital readouts that display current methane concentrations. All of the monitors have three alarm modes: visual (pulsating LEDs), audible (72 to 88 dBa with dominant or fundamental tones in the 2500 to 4500 Hz bands) and vibratory (80 to 120 Hz). Current requirements for methane alarms only include audible or coloured lights (CFR § 30 27.23 (a)). The addition of the vibratory alarm for personal monitors is a feature that will help the recognition of methane in high noise and flashing light work areas. Multiple alarm modes increase the chances that a worker will recognise exposure to high methane levels.

The monitors are small and light enough to be worn by a miner during normal work activities. Any electronic instrument used in US underground mines must be approved however, by Mine Safety and Health Administration for intrinsic safety and performance. All of these instruments do have Underwriters Laboratories and/or Canadian Safety Association approval for use in atmospheres containing flammable methane gas mixtures. Future field study work will include application for experimental permits from MSHA for the methanometers. Upon instrument approval, additional testing will be conducted on-site or underground.

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