Underground Mine Ventilation Air Methane (VAM) Monitoring – an Australian Journey towards Achieving Accuracy

Bharath Belle

Anglo American Metallurgical Coal, Australia

Publication Details
UNDERGROUND MINE VENTILATION AIR METHANE (VAM) MONITORING – AN AUSTRALIAN JOURNEY TOWARDS ACHIEVING ACCURACY

Bharath Belle

ABSTRACT: One of the mining industry’s goals is to establish a standard monitoring device that will primarily monitor gas levels and airflow side by side in real-time to assist as mine safety triggers and in Ventilation Air Methane (VAM) monitoring purposes. Unlike in most Australian mines, continuous real-time air velocity and gas monitoring has been practiced in South African coal mines for over three decades. Envisaged benefits from real-time velocity monitoring over current monthly manual ventilation monitoring are, viz., consistent and continued diagnosis of underground environment and managing catastrophic risks such as fires, explosions, and spontaneous combustion through gas make values; ability to determine real-time carbon monoxide, methane and other noxious gas make, estimation and reconciliation of specific gas emissions during panel development and longwall retreat, determining goaf capture efficiency, accurate determination of heat loads and air cooling capacity, and improving the confidence in ventilation air methane (VAM) emission data. Currently, industry is faced with the persistent and complex challenge of obtaining a ‘reference true gas monitor’ for ‘accuracy’ determination of quintessential VAM parameters, viz., CH4, CO2, air velocity, and temperature. Despite, supplier or external reviewer’s claims, that one monitoring system is superior than the other in terms of its measurement ‘accuracy’, i.e., when compared with the “true measurement device”, in almost all cases, validating these claims was not possible due to lack of data evidence. Therefore, use of measurement system/s that are deemed to provide a practically acceptable, reliable and safe system to provide transparent measurement data is important.

Underground operators are often faced with the famous and simple audit question on an important area of ‘accuracy’, i.e., the difference between ‘true’ value and measured value. There are suggestions of “slight inaccuracies” are being acceptable but currently, no such guidance or value exists. None of the studies or available guidance documents provides guidance on choice of an ‘accurate’ instrument for VAM monitoring. For example, it is acceptable to have an air velocity measurement error of 5 to ± 20 % that are based on research and operational practices. AS2290.3 (1990) outlines an acceptable tolerance measurement limit for instruments. For example, working limit for 1.0 % true concentration of CH4 is 0.91% for real-time (electrochemical /pellistor sensor) with 5% range and 0.90% for tube bundle system with 100% range excluding span gas ranges of ± 0.2%. Considering the above inherent instrument inaccuracies expected, a true measure of instrument performance is to obtain side-by-side results that can demonstrate the difference between the monitoring systems exposed to the same atmosphere. This paper demonstrates that over and beyond the inherent minimal instrument measurement differences, it is those operational factors that are critical to the recording of concentration of gas levels which the instruments are exposed to, viz., airflow that would affect the concentration of CH4 and CO2, barometric pressure, shaft cage effect, longwall coal production levels, magnitude of gas levels, longwall production, which is the main source of the U/G VAM.

INTRODUCTION

Adequacy and quality of controls provided for safe and healthy underground mine environment have been carried out by routine manual measurements of various hazard and control parameters. Mine ventilation is a means of such control and is monitored by manual and instrumentation means to provide assurance on regulatory requirements. In recent times, with the promulgation of Greenhouse Gases (GHGs) have resulted in the need for continuous and accurate monitoring of data. Typically, mines have established an underground Ventilation Air Methane (VAM) emission inventory using manual monthly ventilation survey and continuous monitoring (tube bundle/real-time) data in accordance with the obligations of the National Greenhouse and Energy Reporting Scheme (NGERS) Act (2007).

With the progressive and proactive approach, the practice of once-a-month ventilation survey data and use of underground tube bundle gas monitoring instruments it was identified that they may have limited
ability to record the true gas levels due to their sampling frequency. Issues related to non-emotional data, operator measurement bias and benefits of real-time air velocity versus manual vane anemometer measurement in mines have been studied by various research agencies over three decades (Belle, 2013). Therefore, simultaneous and continuous measurement of airflow, CH\(_4\) and CO\(_2\) levels, absolute pressure and temperature (WBT and DBT) at the same location, was seen to provide the most reliable data. This paper provides the difference between continuous and infrequent variables used in VAM calculations.

While the need for U/G VAM monitoring and reducing its emission to atmosphere, it is important to note that the elimination of methane hazards underground is the foremost requirement of mine safety and prevention of catastrophic explosions. Explosion, fires and Frictional Ignition (FI) risks in coal mines are ever present because of its inherent presence of methane gas (Figures 1 and 2) and these unfortunate events continue to call for embracing new technologies to monitor hazards and take appropriate control responses. In order to minimize the risk profiles of these catastrophic events, it is timely to accept opportunities in the following hierarchical control namely, air velocity (ventilation) monitoring:

![Figure 1 - Statistics on global mine explosions and fires (Belle, 2013)](image1)

![Figure 2 - Comparison of FI incidents in gassy (metallurgical) and low gassy (thermal) mines](image2)
• Accepting the practice of continuous monitoring of the environment of hazards that are continuously changing (read gases and dust)

• Accepting the need for continuous monitoring of air velocity and ventilation controls that are continuously changing (read airflow) regardless of their magnitude in a ventilation network.

• Accepting that in a complex mine ventilation network, frequent manual ventilation monitoring in main returns or intakes is a cumbersome process and has practical and time limitations.

• Accepting the availability of Intrinsically Safe (IS) real-time monitoring tools for underground use in the technologically advanced workplaces.

• Accepting that continuous air velocity monitoring devices u/g can provide leading indicators of expected conditions in the event of a failure or provide early warning of ventilation effectiveness.

• Accepting that traditional measurements aided with continuous monitoring would enhance the response time in the event of emergencies.

• Accepting that approved IS real-time velocity monitors are available in Australia and there is a need in improving the approval process for use in mines.

• Accepting that just as in other real-time monitoring tools, velocity monitors also need maintenance.

• Accepting that continuous velocity monitoring is a leading practice in other parts of the coal and metal mining world (UK, Canada, South Africa, Poland).

• Accepting that improvements in velocity monitoring would assist the mines in controlling and providing improved quality of air.

• Accepting that a real-time velocity monitor is a safety and production enabler.

BACKGROUND TO AUSTRALIAN GAS MONITORING JOURNEY

The U/G VAM is significant constituent (over 70%) of past, current and future underground carbon emissions. The following section summarizes the background of current gas monitoring systems, their shortcomings if any, and the need for the use of real-time continuous monitoring for VAM assessment.

• Australia is probably the only country whereby the mines use extensive network of tube bundle gas monitoring systems that provide frequent data on gas levels for various mine safety triggers during normal and emergency scenarios. Tube bundle gas monitoring is a network of tubes running from the surface to selected underground locations and draws a small volume of air sample from the general body of air to surface and analyses the gas composition through infra-red (IR) analysers at regular intervals.

• Through the years, it has been accepted that both tube bundle and real-time monitors are effective gas monitoring systems with inherent benefits and weaknesses.

• Typically, a tube bundle system using an IR analyser, is seen to be ‘superior or accurate’ because of its reliability during major safety incidents or goaf sealing or as an early warning device for sponcom/fire events. Many a times, due to the number of tube monitoring stations underground, the sampling frequency would vary from every 30 minutes to 60 minutes or higher. However, it can be argued that the cost of superiority or accuracy is at the expense of misrepresenting or sacrificing the sufficient representation of the constantly changing underground gas atmosphere.

• Real-time monitors require sufficient presence of oxygen (available in almost all underground working areas except goaf) to operate which is not unlikely at shaft bottom or exhaust shafts. For the current real-time sensors, measurement range is appropriate and provides results in near real-time unlike infrequent tube bundle monitor data.

• Despite, various supplier, auditor or external reviewer’s claims, that one monitoring system is superior over other in terms of its measurement accuracy, i.e., when compared with the “true measurement device”, in almost all cases, validating these claims was not possible due to lack of data or evidence. As of date, there is no side-by-side comparison of tube bundle or real-time monitor or Gas Chromatography (GC) performance on measuring methane for low, medium and high gas concentration levels. For example, the acceptable air velocity measurement error of
5% to ± 20% accuracy requirements for mine ventilation applications are based on operational practices.

- Despite the above shortcomings, real-time ventilation and gas measurement systems would provide an improved frequency of measurements, incorporate influence of any fan stoppages due to maintenance or power failures, and minimise VAM estimation errors and provide greater confidence in carbon estimates.

- Currently, there is no industry or regulator study that provides guidance or sufficient data evidence on methane measurement accuracy between IR analyser and real-time monitor (point detector) or GC for very low (<0.05%), low (0.05-0.1%), medium (0.1%-0.3%) and high (0.3-0.5%) and very high (>0.5%) concentration levels at exhaust shafts.

- The AS2290.3 outlines an acceptable tolerance measurement limit for instruments. For example, for 15% CH₄ true concentration, acceptable measureable concentration is 14.2%; for 1.0% true concentration of CH₄ is 0.91% for real-time (electrochemical/pellistor sensor) with 5% range and 0.90% for tube bundle system with 100% range. These errors are significant in terms of carbon emission estimates.

- Similarly, for instrument calibration, variations in test gas range for calibration purposes would be in the region of ±0.2% for a “2.5%” true gas. Therefore, inherent errors associated with the test gas, instrument measurement range, laboratory facility may not be superior unless sufficient data is available to validate them. There are suggestions of “slight inaccuracies” being acceptable but currently, no such guidance or value exists.

- None of the ACARP or other regulatory or research documents provides guidance on choice of an ‘accurate’ instrument for NGERs monitoring that would have the ‘accuracy’ values defined in it and comparison has been made with other available continuous monitoring devices.

- An example of SIMTARS study (Brady, 2008) on measured gas levels using gas chromatograph (GC) and tube bundle data (IR analyser) for concentration levels greater than 0.5% methane suggested significant difference between the two analytical techniques. The SIMTARS study did not quantify the differences between the two techniques (IR and GC).

- Typically calibration gas uncertainty is 0.05% to 0.2% range over the ‘true gas’ concentration range of 0.94%, 2.14%, 10.4%, that demonstrates a non-linear relationship. A change in calibration gas may influence the measured values regardless of the instrument used.

AUSTRALIAN JOURNEY OF REAL-TIME AIRFLOW MONITORING ON EXHAUST FANS

The introduction of carbon tax (July 2012) on GHG emission has necessitated the need for accurate airflow data from mine exhaust systems. The significant two variables in the VAM greenhouse gas estimates is the airflow and methane levels. Typically, most mines have established the emission inventory using the accepted manual ventilation measurement practices in accordance with the obligations of the NGERS Act (2007).

The introduction of the NGERS Act provided a significant opportunity in Australian coal mines to build robust, compliant, accurate and transparent VAM reporting through improved real-time airflow monitoring systems instead of the manual monthly ventilation surveys. Mine ventilation engineers have identified the need for a paradigm shift in VAM monitoring systems in terms of resolution and frequency of measurement of key data components even before the common findings from various auditor/reviewer’s opinion on the subject through the years.

With this background, the installation of a monitoring system at exhaust shaft fan ducts to independently measure real-time exhaust airflow, CH₄, CO₂, wet bulb temperature (WBT), dry bulb temperature (DBT), moisture and barometric pressure to comply with NGERS Act (2007) and improve VAM measurement accuracy is becoming a reality. Typically any changes in ventilation system (such as slowing down of fans or power failures) or errors associated with the ventilation measurement are not captured in the estimated carbon emissions. For example, with 400 m³/s of airflow and 0.3% methane, a 10% change in airflow alone would relate to a difference in carbon tax of AUD$1.4 million per annum.

The need to measure the air velocity beyond the statutory measurement location and their frequencies is increasingly becoming a practical reality. The explanations that are faced by the operators (that may be beyond their control) are:
1. Experiencing the art of velocity measurement (years of experience u/g and measurement correlation to monthly ventilation reports)

2. Location of velocity readings taken underground (high velocity turbulent regions or sharp bends)

3. Instruments used and their calibration on surface (Kestrel electronic or manual vane anemometers)

4. Underground environment conditions (humid and dusty vs. comfortable conditions)

5. Time constraints and understanding of ‘value’ of each velocity measurements.

With no means for measuring emissions from the mine in real-time and without compromising current mine monitoring systems dedicated for mine safety, specifically sponcom and explosion prevention, the need for dedicated real-time airflow monitoring at mine shafts is quintessential. Figure 3 shows the implementation of real-time ultrasonic air velocity monitoring system installed on main fan ducts.

![Figure 3 - Installation of real-time air velocity monitoring on main fan ducts](image)

As a proactive approach, most of mines are implementing the approved IS ultrasonic flow monitoring devices at the exhaust shaft fan ducts. It is also noted that a handful of coal mines are in the process of implementing these real-time monitors underground. The introduction of leading practice of real-time monitoring of airflow and low range gas measurements at fan ducts (in NSW and QLD) using real-time analysers to measure the CO2, CH4, and airflow, barometric pressure (BP), WBT, DBT has enabled mines in producing transparent emission reports.

Figures 4a to 4c shows the isovels of main fan ducts measured from four different exhaust shafts with a total of 11 different main fans. These velocity profiles provide a graphical presentation of any issues that can be identified in main fan performance or turbulence associated with the designs. What is valuable is that the velocity contours derived from velocity pressure measurements provide the status of the fan or its future long term use. The isovel plots suggest that they are definitely different to ideal velocity contours obtained in thermodynamic simulations. Furthermore, the velocity contour profiles demonstrate the complexity of recording ‘true’ gas levels in an u/g airway with complex airflow profile being an additional variable that may influence the measurement of gas levels.

The above contours were based on an independent underground Pressure-Quantity (PQ) survey and through mine exhaust fan flow measurements. The objective of this survey was to establish an empirical relationship between real-time ventilation flow data in exhaust fan systems and monthly underground ventilation survey data to enable the use of real-time flow data for underground VAM calculations. Based on independent measurement techniques (manometric, barometric (BP) and vane anemometer), it was established that the variation in manual ventilation flows against the real-time air flows exist. Based on the study, it was noted that the traditional monthly manual and the real-time airflow from the exhaust fan
duct tests for the same period were 511 m³/s and 464.9 m³/s respectively with a measurement error of 46.1 m³/s. Main fan airflow measurement were matching the fan performance curves.

![Figure 4a - Isovels measured at three different fan ducts from an exhaust shaft-A](image)

![Figure 4b - Isovels measured at four different fan ducts from an exhaust shaft-B](image)

![Figure 4c - Isovels for mine Exhaust Shaft 2 (Left) and Exhaust Shaft 4 (right) fan ducts](image)

There are several studies on the use of correction factors (including factory correction factors and the given range of velocities) in the literature; its application in practice is remote. For example Thimmons and Kohler (1985) have suggested that the measurement should be always be made at a minimum distance of three roadway diameters upstream of an obstruction and 10 roadway diameters downstream of an obstruction. In reality, the presence of these ideal locations is scarce or simply they do not exist. Another parameter that is used in determining the airflow is the area of a roadway. Typically, 5% is considered to be an acceptable error during the ventilation survey. Even with this low level of acceptable error the carbon cost is significant, i.e., at 0.2% methane level for a roadway area of 20.30 m², 5% accepted error in area would be costing around $200, 000 per annum. Thimmons and Kohler (1985) have expressed the definitions on accuracy requirements for mine ventilation applications. They had expressed the accuracy of +/− 20% is satisfactory based on the practice of the 1970s.

However, currently this issue is still persisting and the challenge even today. That is which instrument is accepted as a 'reference true velocity measurement device' to determine the accuracy of velocity measurements in mines. Measurement experiences suggest that each operation or a location underground or even the velocity contour profiles of a roadway is dynamic. This suggests that the fixed real-time monitoring systems would minimize the operator error bias against the systematic bias with a fixed velocity monitor.
METHANE MONITORING; TUBE BUNDLE OR REAL-TIME MONITORS

Another parameter in VAM monitoring is the continuous monitoring of airflow through exhaust shafts. Currently, there are approved real-time airflow monitoring systems that are available for exhaust fan shafts. Considering the above inherent instrument inaccuracies expected, a true measure of instrument performance is to obtain the side-by-side results that can demonstrate the difference between the monitoring systems exposed to the same atmosphere. Over and beyond the inherent minimal instrument differences, it is those operational factors that are critical to the recording of concentration of gas levels which the instruments are exposed to, viz., airflow that would affect the concentration of CH₄ and CO₂, barometric pressure, cage effect, longwall coal production levels, magnitude of gas levels, longwall production, which is the main source of the U/G VAM.

In order to demonstrate the importance of these parameters, 15 different longwall panel return side-by-side real-time and tube bundle daily data were statistically analysed. Each daily data was separated into an hourly data and collated into minimum, maximum and average CH₄ levels for both tube bundle and real-time monitoring systems positioned side-by-side. Figure 5 shows the real-time airflow and gas data measured in a longwall panel return, demonstrating the influence of airflow and longwall production on measured ambient gas levels. Figure 6 shows the comparison of side-by-side real-time catalytic sensor and tube bundle (IR) sensor along a longwall panel return demonstrating infrequent data affecting the average gas levels.

![Figure 5 - Real-time airflow and gas data in a LW panel return](image)

Figures 7 to 10 show the relationship between real-time and tube bundle data (daily and hourly) for various gas levels measured over different sampling periods. From the regression lines of daily data, it is noted that the tube bundle system records the methane levels 8% higher than the real-time data. Similarly, hourly minimum real-time data is 82% of the tube data suggesting the low gas levels are not recorded by the tube monitoring system. On the other hand, hourly maximum methane data from real-time monitor recorded 6% higher gas levels than the tube monitoring system as the tube monitor fails to record the peak atmosphere data due to the lower ambient sampling frequency.

STATISTICAL ANALYSES

In order to understand the critical factors influencing the gas levels recorded by the monitoring systems, the hourly methane data recorded during daily longwall production located side by side at longwall panel return was used to perform statistical Analysis Of Variance (ANOVA) and determine significance of main factors and their interactions. The real-time monitor data are also the same value used to verify Trigger Action Response Plans (TARPs) for ventilation and gas management. Typically, methane levels were recorded every 30 sec or less, while the tube bundle data measured approximately every 50 minutes.
The hourly methane concentration data is in the form of $C_{ijklm}$ (%). The subscripts have the following definitions:

i. $i$ = Statistical parameter, $i=0$ is minimum, $i=1$ is maximum and $i=2$ is average methane levels;

ii. $j$ = Methane concentration levels, $j=0$ is 0.5%, $j=1$ is 1 % and $j=2$ is 2.5%;

iii. $k$ = Barometric pressure, $k=0$, 1 and 2 respectively indicate pressures of 98 kPa, 99 kPa and 100 kPa;

iv. $l$ = Daily shift period, $l=0$, 1, and 2 are longwall production periods of 8:00 hr, 16:00 hr and 24:00 hr respectively

v. $m$ = Longwall production, $m=0$ is 7000 tons, $m=1$ is 14,000 tons, $n=2$ is 21,000 tons.

Figure 6 - Comparison of side-by-side real-time and tube bundle in a LW panel return

Figure 7 - Comparison of side-by-side LW panel return real-time and tube bundle monitor (Daily Avg.)
Figure 8 - Comparison of side-by-side LW panel return real-time and tube bundle monitor (Hourly Avg.)

Figure 9 - Comparison of side-by-side LW Panel return real-time and tube bundle monitor (Hourly-Max)

Figure 10 - Comparison of side-by-side LW panel return real-time and tube bundle monitor (Hourly-Min)
The main statistical factors in the study are barometric pressure (including cage effect), daily shift period, longwall production, and level of methane concentration measured and recorded by the real-time and tube bundle monitoring systems. P (probability) - values are often used in statistics, where one either rejects or fails to reject a hypothesis or its significance. The smaller the p-value, the smaller is the probability that one would be making a mistake by rejecting the importance of the factor effects on measured peak methane levels. In the ANOVA (Table 1), some p-values were printed as 0.000, meaning that significant evidence of factor effects influencing the recorded values.

Table 1 - Analysis of variance (ANOVA) for CH₄ data

<table>
<thead>
<tr>
<th>Source</th>
<th>Df</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F statistic</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4-Statistic</td>
<td>2</td>
<td>17,685</td>
<td>0.448</td>
<td>0.224</td>
<td>6.17</td>
<td>0.002</td>
</tr>
<tr>
<td>CH4 Conc. Level</td>
<td>2</td>
<td>250,613</td>
<td>179,459</td>
<td>89.729</td>
<td>2470.39</td>
<td>0.000</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>2</td>
<td>0.574</td>
<td>0.278</td>
<td>0.139</td>
<td>3.82</td>
<td>0.022</td>
</tr>
<tr>
<td>Shift period</td>
<td>2</td>
<td>1.054</td>
<td>1.131</td>
<td>0.565</td>
<td>15.57</td>
<td>0.000</td>
</tr>
<tr>
<td>Production</td>
<td>2</td>
<td>0.728</td>
<td>0.728</td>
<td>0.364</td>
<td>10.02</td>
<td>0.000</td>
</tr>
<tr>
<td>Error</td>
<td></td>
<td>2149</td>
<td>78.056</td>
<td>78.056</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>2159</td>
<td>348.710</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Considering the above results, it can be noted that the above identified factors play a crucial role in measuring the true methane levels, which would require continuous monitoring against intermittent recording by u/g shaft bottom tube bundle systems as they do not represent major factors that would significantly affect the recorded gas levels. The difference in measured concentration levels by real-time and tube bundle data are calculated and are shown in Table 2. These large differences suggest that the inherent accuracy differences associated with the gas monitors are insignificant when compared with the operational factors in measuring the gas levels.

Table 2 - Difference between recorded side-by-side LW return real-time and tube-bundle data (hourly)

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Min CH₄ Difference, %</th>
<th>Max CH₄ Difference, %</th>
<th>Avg. CH₄ Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6</td>
<td>-6.2</td>
<td>-7.4</td>
</tr>
<tr>
<td>2</td>
<td>-33.3</td>
<td>-6.3</td>
<td>-16.7</td>
</tr>
<tr>
<td>3</td>
<td>-12.8</td>
<td>-2.5</td>
<td>-14.8</td>
</tr>
<tr>
<td>4</td>
<td>3.5</td>
<td>2.5</td>
<td>-0.1</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
<td>2.6</td>
<td>-8.7</td>
</tr>
<tr>
<td>6</td>
<td>-12.9</td>
<td>15.9</td>
<td>-4.0</td>
</tr>
<tr>
<td>7</td>
<td>3.1</td>
<td>20.8</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>50.0</td>
<td>19.5</td>
<td>22.4</td>
</tr>
<tr>
<td>9</td>
<td>-72.7</td>
<td>16.9</td>
<td>-22.1</td>
</tr>
<tr>
<td>10</td>
<td>-20.0</td>
<td>7.5</td>
<td>-32.3</td>
</tr>
<tr>
<td>11</td>
<td>100.0</td>
<td>25.7</td>
<td>-10.8</td>
</tr>
<tr>
<td>12</td>
<td>-31.2</td>
<td>28.6</td>
<td>-12.9</td>
</tr>
<tr>
<td>13</td>
<td>-66.7</td>
<td>12.4</td>
<td>-13.3</td>
</tr>
<tr>
<td>14</td>
<td>-90.0</td>
<td>40.5</td>
<td>-11.6</td>
</tr>
<tr>
<td>15</td>
<td>12.5</td>
<td>5.4</td>
<td>1.1</td>
</tr>
</tbody>
</table>

As part of the statistical analyses, side-by-side real-time and tube bundle data were compared. A paired t-test was performed on the set of all the sample pair data to determine if there was a statistical difference in the recorded concentration levels between the monitoring pairs. A paired t-test of hypotheses was developed to compare the mean methane concentration level measured with two monitoring instruments (µᵐᵉᵃⁿₕₑᵃʳlée-timᵉ and µTubeBundle). The null and alternative hypothesis for the tested sample pairs were: H₀: µReal-Time = µTubeBundle and H₁: µReal-Time ≠ µTubeBundle. In the paired t-test, hypothesis H₀ states that the mean methane concentration levels from both monitors (µReal-Time and µTube Bundle) are equal. On the other hand, alternative hypothesis states that the two monitors in fact measure different mean concentration levels. It is therefore necessary to use hypothesis testing to accept or reject H₀. For this work, a standard 95 % confidence level was chosen. As the hypothesis stated were µReal-Time = µTube Bundle and µReal-Time ≠ µTube Bundle, all analyses were two tailed to account for both conditions µReal-Time < µTube bundle and µReal-Time > µTube Bundle. Therefore, the critical t-values were determined by t₀.025 rather than t₀.05. Results of the paired t-test statistical analyses are given in Table 3.
From Table 3, it is observed that, for maximum methane levels, t-statistic $C_{\text{real-time}} - C_{\text{tube bundle}}$ was 4.73. This indicates that recorded maximum methane level from the real-time monitor was generally greater than the maximum methane level from the tube bundle system and the null hypothesis is rejected (p-value of 0.000). A paired t-test was also performed on daily methane data (15 days) to determine if there was a statistical difference in the results obtained between two monitoring systems for different statistical parameter. The result of the paired t-test was a test statistic with 14 degrees of freedom, $t = 0.197$ (Table 4) indicating no difference between the two monitoring devices for minimum gas levels but significant difference on measured levels for maximum and daily average methane levels.

### Table 4 - Statistical comparison of daily real-time and tube bundle data

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Paired T-test</th>
<th>Paired T-test</th>
<th>Paired T-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Real-time$_{\text{Min}}$</td>
<td>Tube$_{\text{Min}}$</td>
<td>Real-time$_{\text{Max}}$</td>
</tr>
<tr>
<td>N</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Mean</td>
<td>0.3113</td>
<td>0.3447</td>
<td>1.673</td>
</tr>
<tr>
<td>$\mu_{\text{real-time}} - \mu_{\text{Tube}}$</td>
<td>-0.0333</td>
<td>0.2487</td>
<td>-0.0503</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>0.1998</td>
<td>0.2303</td>
<td>0.645</td>
</tr>
<tr>
<td>SE Mean</td>
<td>0.0516</td>
<td>0.0595</td>
<td>0.166</td>
</tr>
<tr>
<td>95% CI for $\mu$</td>
<td>(-0.0861, -0.0194)</td>
<td>(0.0811, 0.4162)</td>
<td>(-0.0940, -0.0065)</td>
</tr>
<tr>
<td>T-Value</td>
<td>-1.35</td>
<td>3.18</td>
<td>-2.47</td>
</tr>
<tr>
<td>P-Value</td>
<td>0.197</td>
<td>0.007</td>
<td>0.027</td>
</tr>
<tr>
<td>Hypothesis</td>
<td>Accept $H_0$</td>
<td>Reject $H_0$</td>
<td>Reject $H_0$</td>
</tr>
</tbody>
</table>

Although the two commonly used monitors differ according to their design, operation, cost, maintenance, frequency of sampling, and ease of use, the hypothesis tests results of the methane data have demonstrated that significant difference in the relative mean methane levels are recorded in the longwall panel return between two monitoring systems. However, for maximum methane values, CH$_4$ levels from the real-time monitor were generally higher than the CH$_4$ level measured by the tube bundle system. This does not hold true for the minimum and average data, where the concentration value obtained by the real-time monitor was less than by the tube bundle system.

Furthermore, Relative Standard Deviation (RSD) values between real-time and tube bundle systems were calculated. The measured overall variability includes all the variability associated with location of the monitoring systems in a sampling environment, as well as spatial and temporal variability that occurs underground during various production scenarios. The overall variability for each monitoring system accounts for all variability introduced by real-field effects and is based on valid statistical methods. This measured variability includes the inherent instrument sampling error, measurement error (fixed sample), and daily or hourly variability of methane concentration, and represents the best estimate of the long-term variability to quantify the measured concentration levels. The smaller of the overall variability is a more appropriate parameter to use when selecting the monitoring system for assessment. The RSD values for real-time and tube bundle using daily average methane data were 0.358 % and 0.367% of methane respectively. This further demonstrates that for VAM calculation purposes, a monitoring system with the minimal variation and that records continuous and frequent detection is a preferred choice.
CONCLUSIONS

Air velocity and area of a roadway, WBT, DBT, CH4, CO2, BP are the key parameters that will assist in understanding the key hazards (gas, dust, sponcom, thermal), associated risks and the effectiveness of controls provided at workplace. Therefore, it is important that these parameters are accurately measured by those who are responsible for them.

The monitoring of air velocity at strategic positions assist in U/G VAM monitoring purposes instead of the monthly single surveys, which fail to record reduced air flow conditions or stoppage of fans for maintenance and thus fail to record the ‘true’ airflow and GHG estimations. Also, they will indicate the status of the air distribution in the mine on a continuous basis. The velocity monitors will give early warning of a weakening in airflow or a ventilation failure and timely action can therefore be taken before a gas accumulation develops. Benefits of real-time velocity monitors will provide the ventilation engineers additional information on whether the increase in gas levels is due to increase in gas release rate or reduced ventilation.

In an underground environment or exhaust shaft, the ideal ‘true monitor’ would measure the atmosphere that represents the mine methane levels accurately. In this study, it is noted that ‘accuracy’ of a specific monitoring system was not possible in the absence of an approved ‘true reference monitor’ or acceptance criteria currently available in the mining or gas measurement industry. Since the real-time monitor measures the gas levels in near real-time, its use as a ‘true reference monitor’ is justified as it records the changes in gas levels that are affected by various mining related parameters which are not monitored by the current intermittent tube-bundle monitoring system at underground locations such as shaft bottom or exhaust shaft.

The maintenance of an environmental monitoring system is of vital importance as the confidence in the system will be lost if the system is not maintained. All existing real-time and tube bundle systems require adequate maintenance as per the Australian Standard 2290.3 (1990). Failure to address will lead to misinterpretation of conditions underground and should be addressed without delay by relevant responsible person for the installation and maintenance of the monitoring systems. As in the case of existing gas monitoring systems, the inspection should include cleaning of monitors, testing of response of monitors, replacing malfunctioning monitors, a documentation system to include installation, cleaning, testing and date of replacement.

Based on the compelling evidence of data as demonstrated using the side-by side data analyses of two monitoring systems at LW panel return location, viz., real-time and tube bundle, it is noted that the tube bundle system records significantly higher daily average gas levels than the real-time monitors by approximately eight per cent. This difference in values can be attributed to the tube bundle system not sampling of atmosphere on a continuous basis.

For the statistical parameters of interest for U/G VAM calculations, minimum, maximum and daily/hourly average methane data, the per cent difference between the two monitoring systems is over and beyond the ‘accuracy’ differed inherent between the two systems, i.e., tube bundle and real-time catalytic sensors. Finally, for VAM determination purposes, based on the overall variability calculations (RSD values), a monitoring system with the minimal variation and that records continuous and frequent detection such as real-time monitor is a preferred choice.

WAY FORWARD

Mines should be safe places in which to work and any drivers that will endanger the safety and lives of underground worker to minimize the GHG emission through surface gas drainage networks need to be avoided. An opportunity to improve the underground ventilation and gas monitoring system (robust, complaint, accurate and transparent) by using continuous real-time air flow and gas measurement devices has been identified, viz.,

1. Based on the independent fan test evaluations, and the data analyses carried out in this study, it is recommended that mines implement real-time airflow, IR continuous gas (CH4 and CO2) analyser, BP and temperature monitors at exhaust shaft fan ducts for underground ventilation air methane (VAM) estimations.

2. Currently, industry is faced with the persistent and complex challenge of obtaining a ‘reference true monitor’ for accuracy determination on quintessential U/G VAM parameters, viz., CH4, CO2,
air velocity, and temperatures. Also, evidence of supplier claims of ‘accuracy’ between the various monitoring systems is not readily available despite views of external auditors and reviewers. Therefore, operations are using the system/s that is deemed to provide practically acceptable, reliable and safe system to provide transparent UG VAM data.

ACKNOWLEDGEMENTS

Author is indebted to various sources of knowledge that were developed in the past that have resulted in a better understanding of U/G VAM measurement and reporting in mines.

REFERENCES

Belle, B., 2013, AA Internal FI and Global Methane and Coal Dust Explosion Database, Australia. Brady, D., the influence Analytical techniques and Uncertainties in Measurement Have on the Assessment of Underground Coal Mine Atmospheres, SIMTARS.