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PERFORMANCE ANALYSIS OF SURFACE GOAF GAS DRAINAGE HOLES FOR GAS MANAGEMENT IN AN AUSTRALIAN COAL MINE

Bharath Belle[1,2] and Guangyao Si[2]

ABSTRACT: This paper focuses on assessing gas drainage performance from vertical surface goaf holes in an operating mine with high specific gas emission rates (~20 m^3/t). Field monitoring results of gas flow rate and gas composition collected from individual gas drainage holes were analysed. The major challenge of implementing the full potential of goaf drainage system is the perceived risk of spontaneous combustion (sponcom) in goaf using *arbitrary trigger set points*. Although the provenance on the introduction and reasons for the use of CO is unknown, the paper highlights that the current use of CO based trigger action response plan (TARP) for sponcom management leads to the premature closure of goaf holes, which largely constrains goaf hole gas drainage performance and has a significant bearing on longwall gas management. The CO concentration in gas captured by goaf holes is found to be positively correlated with O_2 concentration and negatively correlated with CH_4. Building upon abundant field measurement data, goaf gas profiles for CO, O_2, CH_4 and CO_2 concentration were established, which suggest that the increase trend of CO level behind the face is a normal behaviour of goaf closure and would recover to trivial concentration after 300 m deep into the goaf. The paper provides the basis to eliminate or review the use of CO triggers in current surface goaf gas management TARP levels of longwall panels, which has detrimental effect on longwall TG gas management for explosion prevention.

INTRODUCTION

Coal has been a primary source of global energy production and development for the past two centuries and is expected to continue into the near future. Today, coal supplies 40% of global electricity, and in some countries such as South Africa and China, it supplies over 90 % and 70% respectively of the electricity generating source. In the case of Australia, its association with coal can be traced back to as early as 1797. Methane is a major gaseous constituent of the coal seam. It gets released during mining and can result in unsafe working conditions.

Methane is explosive in the range of 5% to 15% in air, its transport, collection, or use within this range, or indeed within a factor of safety of at least 2.5 times the lower explosive limit (2.0%) and at least two times the upper limit (30%), is generally considered unacceptable because of the inherent explosion risks. Methane is contained under pressure within the micropores and fractures of coalbeds and in the adjacent strata and gets released into the mine atmosphere during mining (Moore, Deul and Kissell, 1976). The removal of methane by conventional ventilation is particularly difficult in Longwall (LW) mining of gassy coalbeds, which are prone to dangerous outbursts. In Australia, typically, pre-drainage of working seam would entail management of the outburst risks by ensuring the gas content values below 7 m^3/t as one of the rule-of-thumb outburst risk indicators. A combination of pre- and post-drainage using advanced, Surface-based In-Seam (SIS), Medium Radius Drilling (MRD) and Underground In-Seam (UIS) directional drilling techniques are utilised in Australia (Belle, 2017).

Goaf is a broken and loose, highly permeable ground where coal has been extracted by coal mining and the roof has been allowed to collapse, thus fracturing and de-stressing strata above

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and, to a lesser extent, below the seam being worked. In a typical U ventilated longwall coal mine, the goaf gas is generated from the broken and left over coal as well as the liberation from the upper and lower coal seams adjacent to the working seam. When these goaf gases are not managed, they will enter into the general body of the ventilation return air by means of goaf fringe on the tailgate side of the longwall. It is important to note that with limited longwall ventilation dilution capacity, ensuring adequate and timely goaf drainage is critical. In multi-seam longwall mining, goaf drainage plays a fundamental and critical role in managing the gas levels. The volume of gas in the post mining depends on the thickness of upper coal seams, gas content, rate of longwall retreat, gas purity, magnitude gas domain. Generally, the volume of goaf gas is significantly higher than the pre-drainage of the working seams. Typically, goaf drainage holes used are as follows, viz., horizontal boreholes, cross-measure boreholes and vertical surface goaf holes. For longwall retreat mining, surface vertical goaf boreholes are drilled from the surface into the upper limits of the goaf, collecting goaf gas from the de-stressed goaf area. Vertical goaf holes are the most appropriate, efficient and safe methodology where there is surface access to an operating longwall mine. Where there was a failure of surface goaf holes, attempts have been made to access the goaf space using 203 mm (8 in) drainage pipes through perimeter roadway seals (Belle, 2017) under controlled Trigger Action Response Plan (TARP) values for methane purity and oxygen levels for safe and effective longwall mining.

The provenance of the introduction of CO (carbon monoxide) as a trigger for sponcom management is unknown or not well documented. Anecdotal discussions suggest that they are an indication of sponcom activity in the active and sealed longwall goaf. It is measured and documented the presence of elevated levels of oxygen behind the goaf as a result of the used ventilation system. The presence of this oxygen under very humid and hot conditions enable the left-over broken coal behind the longwall chocks leading early coal oxidation. If not monitored and controlled, this condition may turn itself into elevated levels of heating leading to sponcom fire. Therefore, to prevent potential sponcom hazards, underground seal gas compositions are measured for sponcom indicator gases.

The current goaf gas drainage practice in Queensland mines also monitor the gas composition in particular CO levels in individual goaf holes to stop the goaf hole operation. Although CO level in ventilation air acts as a robust trigger value for sponcom control in underground ventilation system, it is unclear whether CO level in drained goaf gas also would provide an accurate trigger for sponcom incidents in the goaf. Building upon the analysis of gas drainage performance from goaf holes at a high production gassy mine, this paper reviews the performance of goaf drainage holes and their gas composition to manage the tailgate gas levels as well as reviews the relevance of the current CO-based TARP for sponcom management in goaf holes.

GOAF HOLE GAS DRAINAGE AND SPONCOM TARPS

This section of the paper provides the background to the goaf hole spacing and their performance in managing the methane gas levels in a high production longwall operating mine. In the recent panels, in order to maintain ventilation and gas regulatory compliance, a disciplined data collection system was established, which includes total goaf gas flow and composition from each of the goaf holes, underground longwall real-time gas, ventilation airflow, barometric and production. These have enabled operators to understand the goaf gas dynamics, location of gas zones and anticipate controls and optimise future drainage programs. The results and analyses carried out on three longwall panels (LW6, LW7, and LW8) are based on this data collection system, with particular reference to goaf gas flow, gas composition and use of CO levels as a trigger for sponcom management. Typically, the manual goaf hole gas composition parameters are used to slow down or shut-off individual goaf hole operation.

This paper will focus on analysing data collected from a representative panel LW7 along with additional two LW panels. There are in total 92 goaf holes in the LW7 panel. Among these goaf holes, 71 were drilled a 30-40 m away from the tailgate roadway with ~50 m spacing, while 21 holes were drilled 50 m away from the maingate (MG) with ~150 m spacing (Balusu, 2016). From inbye to outbye, the goaf holes at the Tailgate (TG) side were named as 7-01 to 7-71, and the goaf holes at the MG side were named as 7-MG01 to 7-MG21. Typical goaf holes would have been fully cased in the top portion and the bottom 48 m of the holes were cased with slotted pipes to allow gas flow into the pipes. The diameter of these goaf holes was 250 mm (10") and their length was 330 m with bottom hole completion depth at 10 m above the coal seam. The first tailgate goaf hole was approximately 25 m from the start-up line.

GOAF HOLE PERFORMANCE ANALYSIS

Overall performance

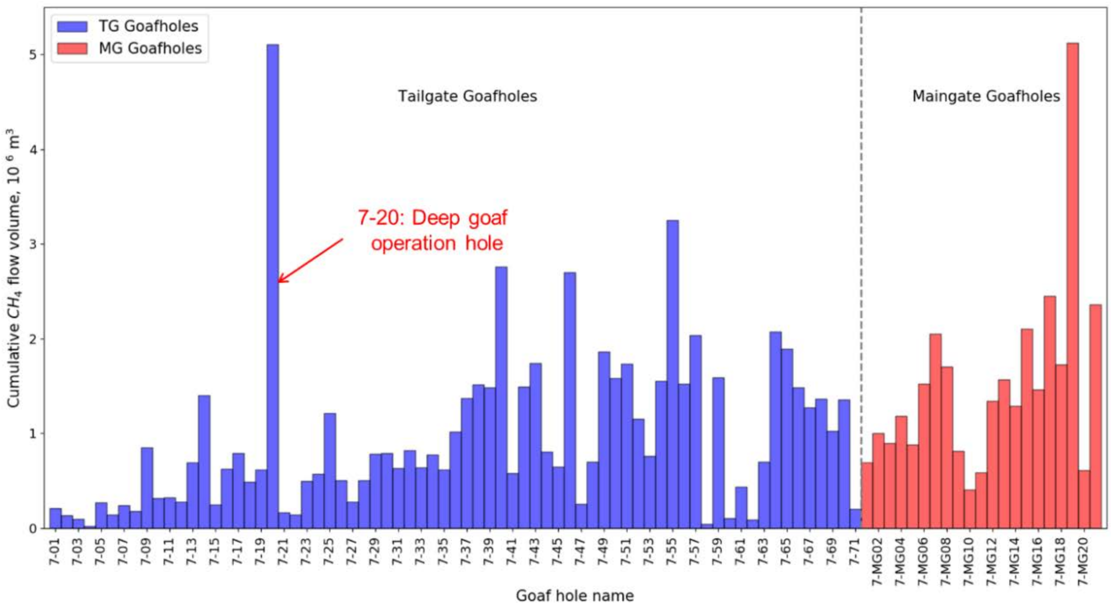


Figure 1: Cumulative flow volume in individual goaf holes from inbye to outbye at LW7

The following paragraphs provide analyses of LW7 goaf hole performance analyses. A large variation of cumulative flow volume in individual goaf holes can be observed across the entire LW7 panel (Figure 1). Goaf hole 7-20 and 7-MG19 achieved more than 5×10^6 m^3 methane production while in goaf holes such as 7-04 and 7-58, the cumulative methane flow volume was less than 5×10^4. Average methane flow rate and methane concentration of drained gas in individual goaf holes are shown in Figure 2, which also suggests a large variation of the purity and efficiency of goaf gas drainage in different holes. A general increase trend of methane purity can be observed as goaf holes move from inbye to outbye at both TG and MG sides of this panel. Gas drained from tailgate goaf holes ranging from 7-01 to 7-19 at the start-up stage shows low flow rate and methane purity due to incomplete goaf cavity formation and lower Specific Gas Emission (SGE) levels along the inbye portion of the panel. On the other hand, methane flow rate in goaf holes 7-47 to 7-63 is relatively low, but they have much higher methane purity. The lower flow rate could be attributed to hole blockage and failures.

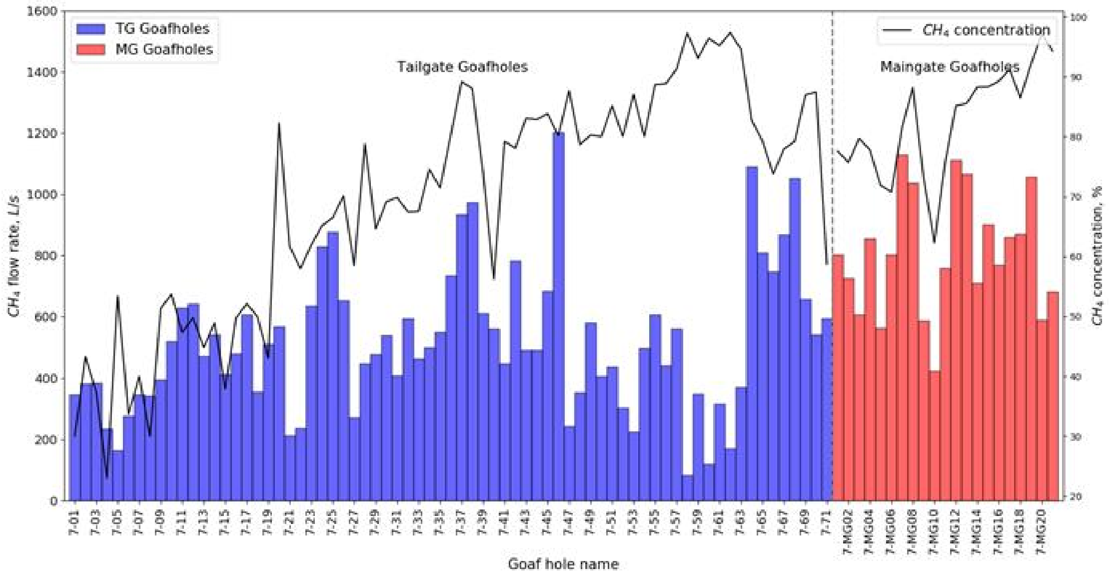


Figure 2: Average methane flow rate in individual goaf holes

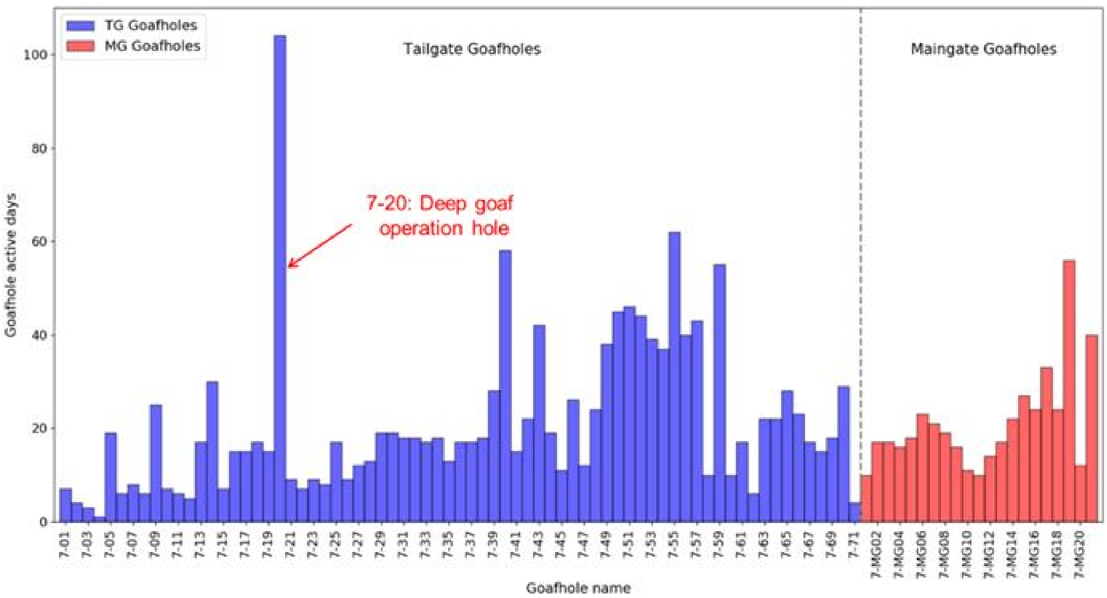


Figure 3: The active production time for individual goaf holes

Goaf holes were opened sequentially along with the progress of longwall face retreat. There is no standard prescribed procedure to shut-off these holes, but CO is seen to be the main reason for premature shut-off. The average active production time for each goaf hole was approximately 21 days as shown in Figure 3. Note that a certain number of goaf holes with extremely short active days, particularly 7-01 to 7-19, were result from the high concentration of CO observed (>60 ppm) in those goaf holes. This led to the premature closure of those holes due to the concern of sponcom activity and the lower CO trigger values used in the goaf hole TARPs. Although flow rates were much lower as observed in goaf holes from 7-47 to 7-63, a much longer active/production days (>40 days) was achieved in these holes due to high methane purity and low CO presence. Note that two goaf holes (7-20 and 7-MG19), which achieved the best gas drainage performance, accredited to the long production period, stable methane flow rate (>400 l/s) and high methane purity (~90%).

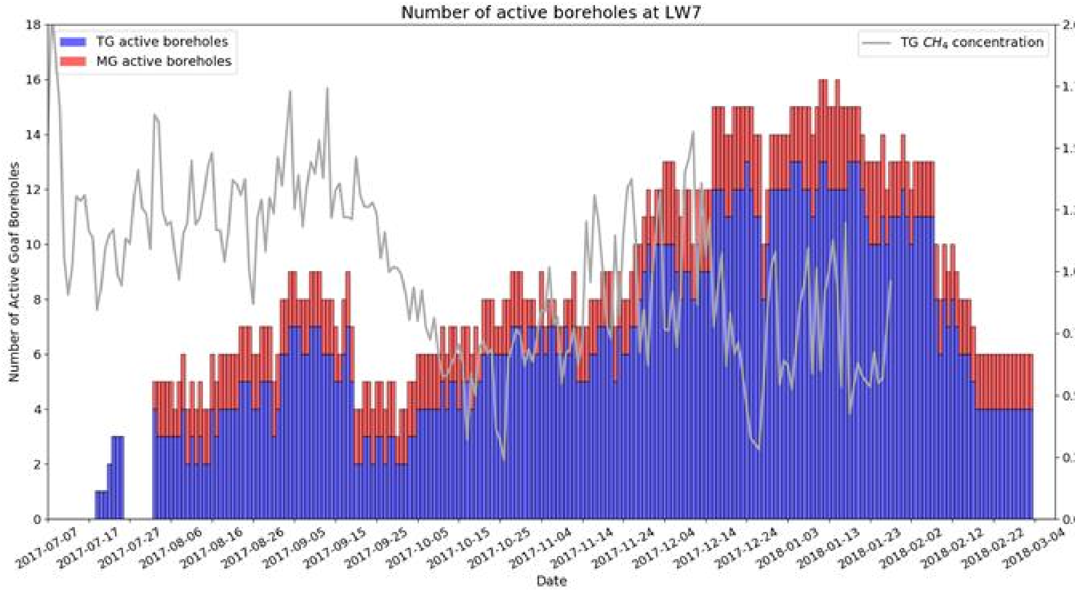


Figure 4: Number of active goaf holes at each longwall production day

The number of active goaf holes in each coal production day during the lifespan of LW7 panel is shown in Figure 4. As explained in the previous figure, in the start-up stage between 17 July to 17 Sep 2017, the low life span of goaf holes results in less active holes (~6) and higher CH_4 concentration observed in the tailgate (~1.25%). On the other hand, there were 14 active goaf holes in average between 2 Dec 17 to 2 Feb 18, which significantly reduced CH_4 concentration in tailgate to ~0.75%. This further demonstrates that with increased size of the goaf gas reservoir, it is important to increase the number of deployable goaf holes to manage the TG gas levels.

Histograms of average methane flow rate and average methane purity in each goaf hole are shown in Figure 5. The average methane flow rate in over three-quarters of goaf holes is higher than 400 L/s and nearly 65% of goaf holes presented methane purity higher than 70%. In general, compared with the TG side, goaf holes drilled at the MG side have better gas drainage performance in terms of higher methane flow rate and methane purity. This can be attributed due to MG holes having access to larger source of gas reservoir from adjacent undrained panels.

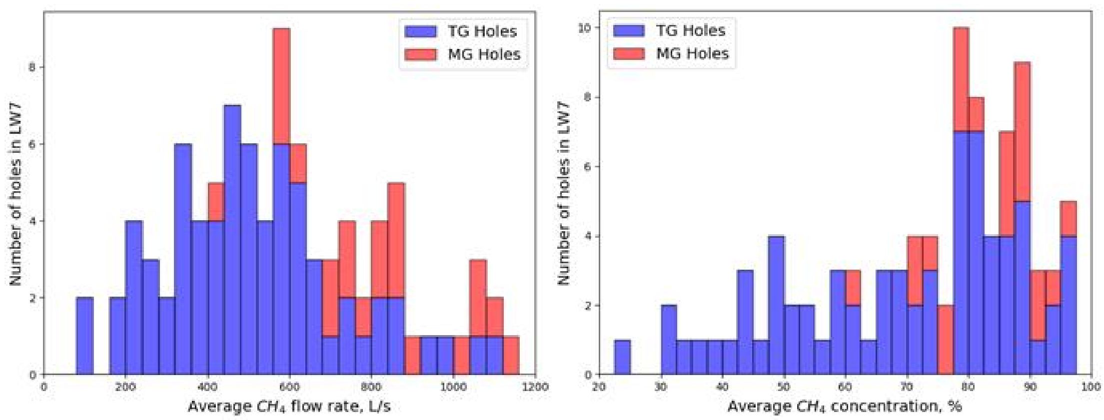


Figure 5: Histograms of number of active goaf holes as the variation of average methane flow rate and concentration

Methane production curves for a number of goaf holes are shown in Figure 6, where side by side (linear neighbouring) goaf holes were plotted. In general, neighbouring goaf holes presented similar gas production trend. Among all goaf holes, a sharp increase of methane production rate was observed within the first five production days. Peak flow rate normally achieved at the fifth production day and then was followed by a gradual decline until the 20th day. If the goaf hole was still active, a long and stable tail with around 400 l/s methane flow rate would be generally observed. The long and stable tails from these methane production curves suggest most of the goaf holes in LW7 were prematurely switched off using either CO TARP or the need to deploy the well-head for the next outbye hole, were seriously under-performing and there is significant potential to increase goaf hole performance by extending their drainage lead time and thus assisting the management of longwall TG gas levels.

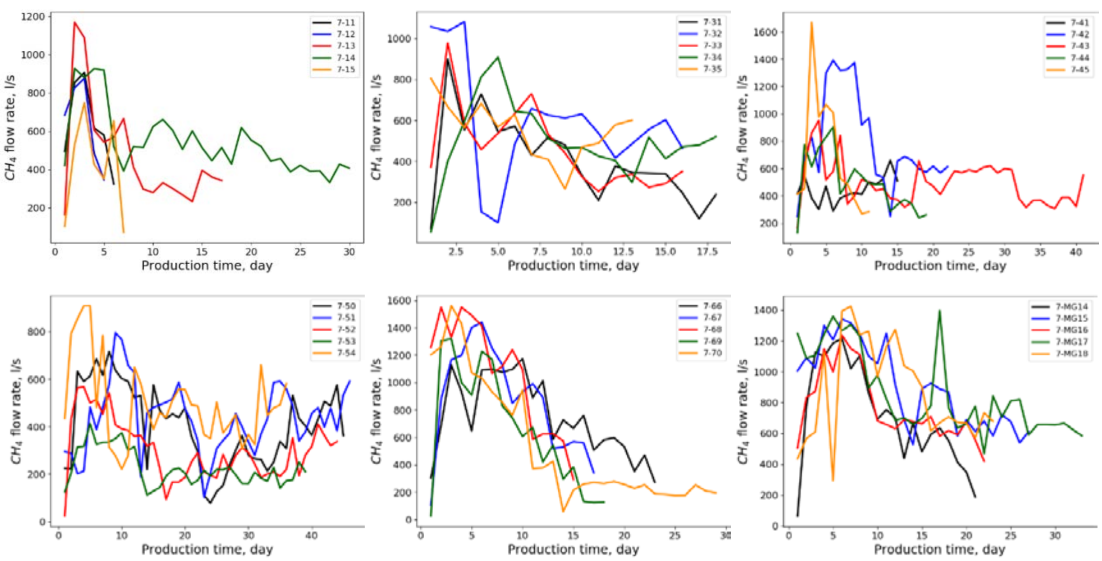
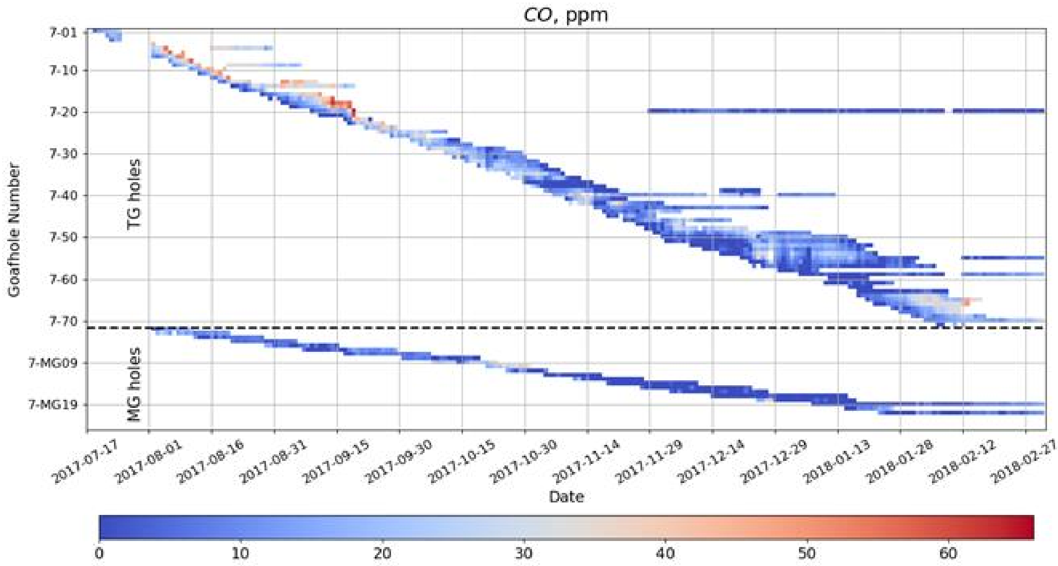


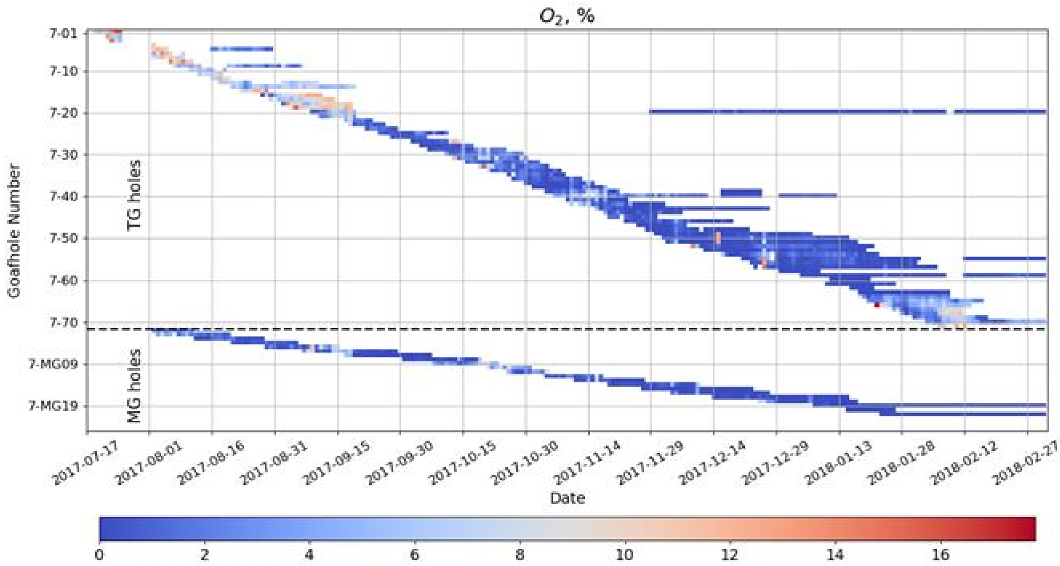
Figure 6: Methane production curves in side by side neighbouring goaf holes

GOAF HOLE GAS COMPOSITION ANALYSIS

The following paragraphs provide an analysis of gas composition of monitored goaf holes. For each goaf hole, the daily captured gas composition was manually monitored over its production period. Heatmaps illustrating the concentration of CO, O_2, and CH_4 for all the tailgate and MG side goaf holes are shown in Figure 7. Each small colour-coded block in these heatmaps represents gas level for a specific goaf hole at one production day. Non-active goaf holes or production days are not coloured. Thus, for each goaf hole, the horizontal length of coloured blocks represents the active operation time (days) of that hole. Similarly, at each production date, the vertical length of coloured blocks represents the number of active holes on that specific day.

As expected, a strong correlation between CO, O_2, and CH_4 levels can be observed, i.e., O_2 percentage is positively correlated with CO and negatively correlated with CH_4. As expected, at the start-up stage of the panel, a high percentage of O_2 was repeatedly monitored in corresponding surface goaf holes, in particular at the TG side, which coincided with the higher levels of CO and consequently the early termination of these holes as a result of TARPs. Higher levels of CO and O_2 measured during the goaf hole start-up is merely a reflection of goaf gas composition immediately behind the longwall face of coal oxidation. It may be possible that the higher velocity of goaf gas flowing past the upper seams may also be contributing to CO generation. There is a misperception that the CO levels recorded is an indicator of elevated levels of sponcom activity in the active goaf. However, based on the recent sponcom incidents of coal mines in Australia, it is suggested that the measured CO levels are an order of up to 1000 ppm higher than the levels recorded from the active goaf drainage holes. Similarly, the CO levels recorded in the Goonyella longwall seam are higher than the German Creek seam longwall. Note that the goaf hole 7-20 was shut-off at the early stage due to high CO but reopened after two months and only a negligible amount of CO was found after re-opening the goaf hole. From mid of October 2017, O_2 level was largely reduced along with a notable improvement in CH_4 purity and production time. During the panel completion stage (early February 2017), another CO increase trend was observed in outbye goaf holes 7-64 to 7-71. Note that high CO or low CH_4 blocks tend to cluster at neighbouring goaf holes or consecutive production dates, which indicates the spatial and temporal continuity of drained gas quality.





The average CO, O_2 and CH_4 concentration over the lifespan of individual holes are shown in contour plots in Figure 8, where the correlation between three gases can also be observed. Goaf gas drainage data collected from LW6 and LW8 were also used here to generate these contours. Note that tailgate goaf holes close to the face start-line (within 800 m outbye) tend to have high CO, high O_2 and low CH_4, which reflects the challenging CO condition during the start-up period and they are certainly not reflective of heightened spontaneous combustion activity. Also, there is no correlation between underground bag samples from sealed areas and goaf hole CO levels. Similar gas composition was observed in goaf holes next to each other, which suggests the gas drainage performance for goaf holes are also spatially correlated.

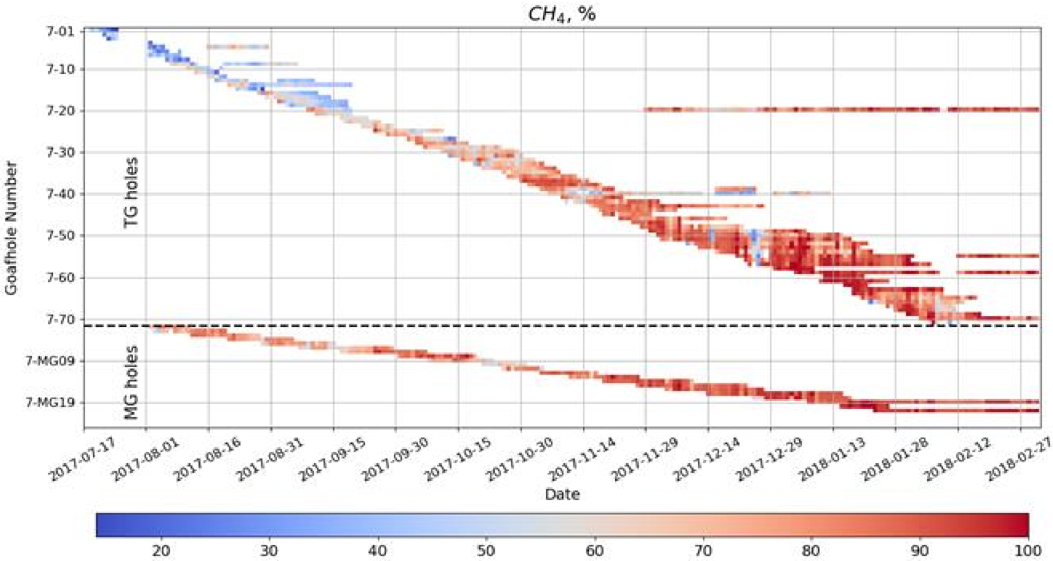


Figure 7: Composition of drained gas in all goaf holes during the LW7 retreating period

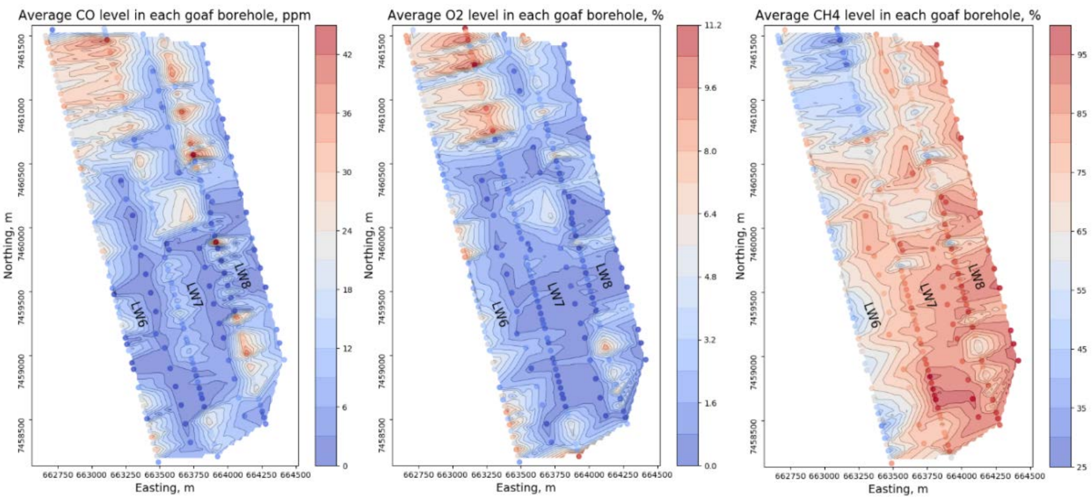


Figure 8: Contours of average gas levels of individual goaf holes during each production period in LW6, LW7 and LW8.

A closer view to examine the goaf holes which experienced high CO issues is shown in Figure 9:, where the CO level increased gradually over time and a similar increase trend of O_2 ingress and decline trend of CH_4 purity were also observed. With the presentence of 10% O_2 in the start-up stage goaf holes, it took approximately 15 days from the first observation of CO until the CO concentration reached the goaf hole shut-off threshold. While for completion stage goaf holes with lower O_2 level, a much longer oxidation time was required, and the maximum CO level was also lower. Compared with the delayed response of CO level, the presence of O_2 or the drop of CH_4 purity suggest that the longwall retreat gas reservoir area is of low rate of gas emission and goaf hole is operating just behind the longwall faceline collecting the oxygen rich goaf gas. It is to be noted that in these longwall panels, there is no large volume of coal gets left in the longwall goaf. Based on the goaf gas analyses of historic 17 LW panels, the use of CO levels from goaf holes have not provided any relationship between underground sponcom activities. On the other hand, the use of lower level CO triggers based on coal gas evolution tests have resulted in premature shut-off the goaf holes resulting in elevated TG gas levels.

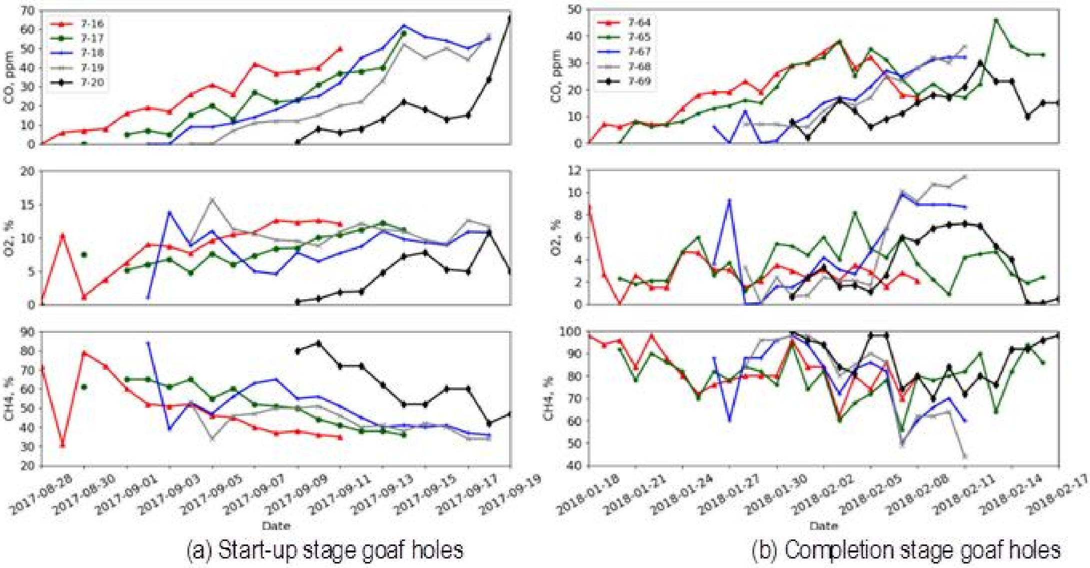


Figure 9: Gas level trends in goaf holes with high CO concentration issues.

Goaf gas profiles

The gas composition measurement results from goaf holes at different distances pertinent to the longwall face during the start-up period (July to September 2017) and completion period (Dec 2017 to Feb 2018) are plotted in Figure 10 and Figure 11, respectively. A clear trend of gas profiles can be observed in the goaf during these periods, which are consistent with the field observations. As discussed earlier, the observation of high CO level led to the premature shut-off of goaf holes, which largely limited their degasification effect. However, according to goaf gas profiles, the presence of high CO level is most likely due to the natural behaviour of goaf closure, which is characterised by an active zone close to the face and an inert zone far deeper in the goaf.

From the gas profiles in Figure 10 and Figure 11, it can be concluded that the active zone is around 300 m wide and the inert zone is from 300 m beyond in the deep goaf and these would vary from mine to mine. As moving deeper into the goaf, the active zone shows an increase trend of CO and CO_2, a relatively high level of O_2, and a mix of CH_4 level response. The gradual increase of CO level in the active zone is a reflection of normal coal oxidation in an oxygen-rich and high moisture and hot goaf environment. On the other hand, in the inert zone, a general declining trend of CO and O_2 can be observed, together with an increase of CH_4 and CO_2 concentration in deeper goaf. This indicates the continued emission of methane from the upper and lower destressed coal seams in the deep goaf and depletion of O_2, which leads to the progressive decline of the CO level.

The identification of the active zone and its behaviour is of significant importance for the goaf gas drainage plan since it defines the 'normal' trend of gas behaviour in the goaf. The observed relatively high CO level in goaf holes may not be a sufficient shut-off trigger if these holes are in the active zone (ranging from 100 to 300 m behind the face). Furthermore, it is imperative to extend the degasification period of goaf holes since once these holes are 300 m behind the face (in the inert zone), they can produce a much purer methane flow with no association to sponcom activity.

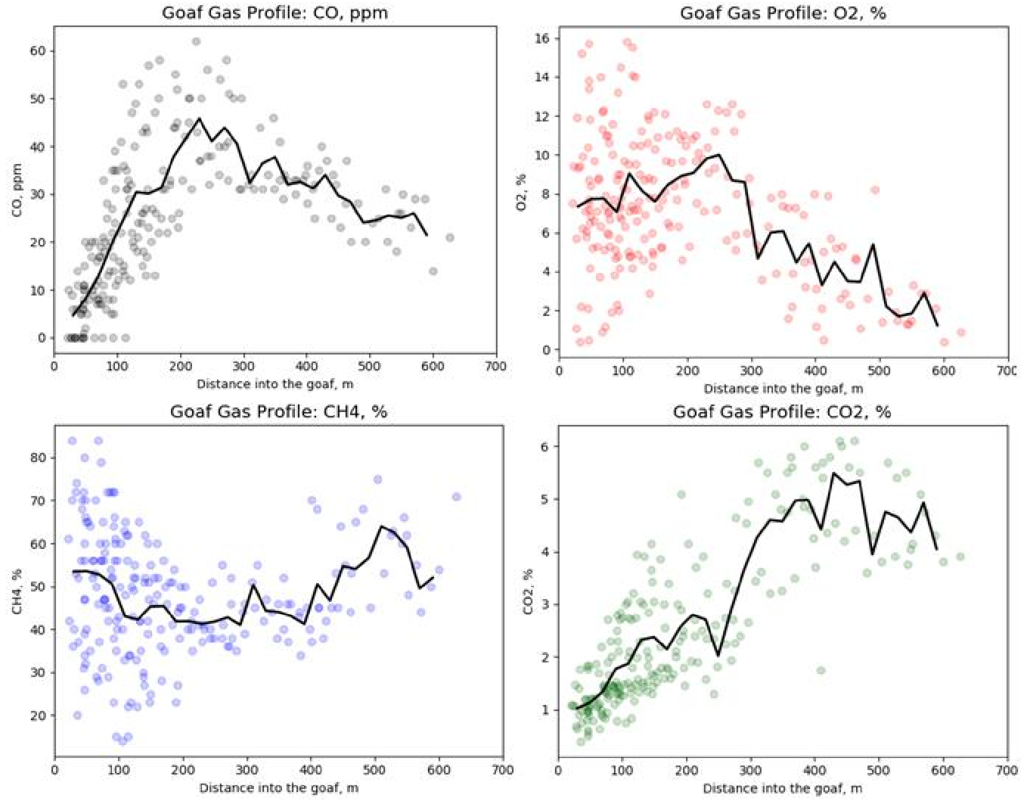


Figure 10: Goaf gas profiles from goaf holes at different distances pertinent to the longwall face during the start-up period (17/07/2017 to 17/09/2017).

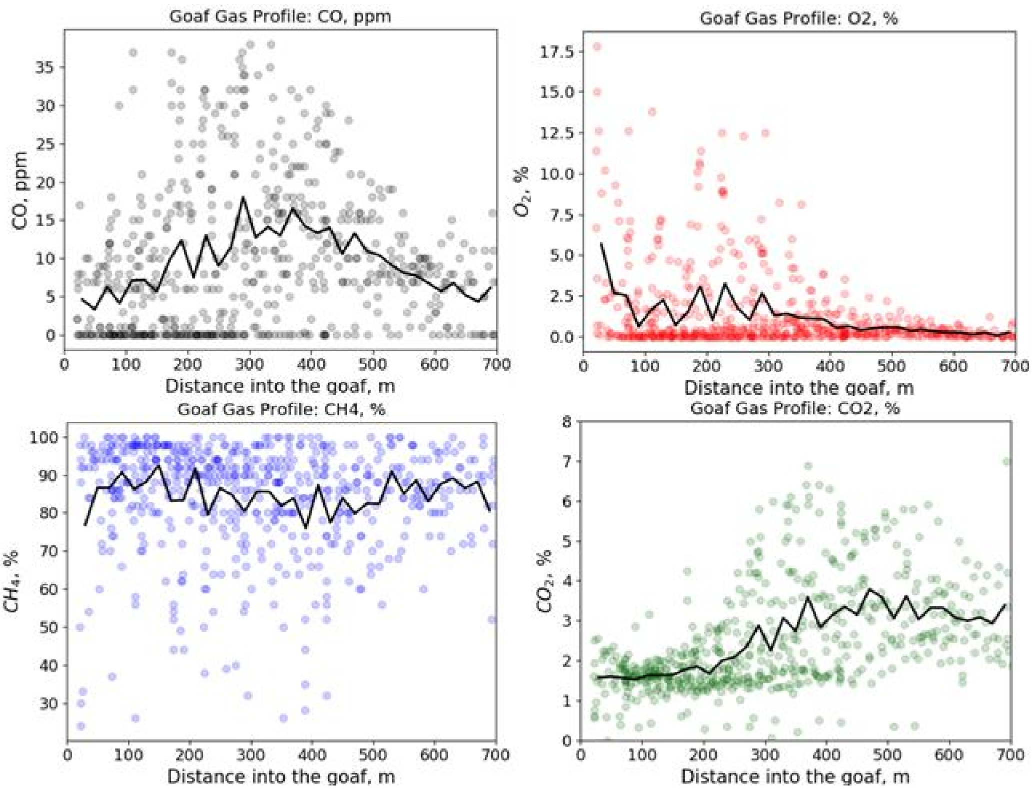


Figure 11: Goaf gas profiles from goaf holes at different distances pertinent to the longwall face during the completion period (12/12/2017 to 12/02/2018).

DISCUSSION

The current operational time for most goaf holes is too short with an average gas production period of 21 days with some holes operated for less than five days. All methane production curves in Figure 6 suggest the existence of a long tail with ~400 l/s methane flow rate and over 90% methane purity. A number of goaf holes with long production periods (7-20 and 7-MG19) also confirm that there is a large potential to increase the production period to 60-100 days without compromising methane quality or the presence of spontaneous combustion risk. In addition, as noted above, a goaf hole with longer production period also indicates that the face would be able to move further away from that hole and result in less volume of O_2 ingress.

Goaf holes drilled in the panel start-up region and completion region observed high level of CO concentration. The high CO level triggered the premature closure of goaf holes, particularly in the start-up region due to the TARP. These problematic goaf holes had relatively low methane flow rate at low methane purity. Goaf holes with low flow rate but high methane purity were also observed, such as 7-47 to 7-63, and these holes tend to have long active time. Goaf holes at the side generally have higher flow rate and higher methane purity compared with goaf holes at the tailgate side.

High CO concentration is a direct result of ventilation air migrating behind the retreating longwall and further ingress into goaf holes. Rich air (O_2) flow observed in goaf holes provides an environment for the slow coal oxidation as well as heat accumulation around the goaf hole vicinity. This leads to a delayed response of CO release and consequently observed in captured gas. The air sucked in goaf holes was most likely from ventilation air leakage while fresh air passed through the longwall face. It is reasonable to anticipate that as the face moves away from a goaf hole, the amount of ventilation air migrate to that goaf hole will be much lower. This can be validated by goaf gas profiles (Figure 10 and Figure 11), where CO/O_2 level dropped and CH_4/CO_2 level increased as the face moved 300 m away from that hole. While the reason behind the introduction of CO level trigger to switch-off the goaf holes is not known, it has certainly affected negatively on the optimum goaf hole operation to minimise the TG gas levels. Therefore, it is recommended to re-consider the usage of CO level in TARPs to switch off the goaf holes or consider the possibility to measure goaf gas temperature as an indicator of the elevated level of coal oxidation.

The current CO-based TARP resulted in the premature closure of a large number of goaf holes in the study mine. Findings from this data analyses suggest it is arguable to not simply use CO as the TARP for identifying spontaneous combustion activity to shut-off goaf holes. A number of reasons are summarised below:

- The release of CO from the coal oxidation process is a delayed response, which requires time for CO percentage to accumulate to the trigger level. Compared with CO, the consistent presence of O_2 in drained gas can be observed earlier and should also be taken into consideration regarding the potential elevated levels of coal oxidation process.
- The progressive longwall retreating causes dynamic changes to CO, O_2, CO_2 and CH_4 levels. For a goaf hole at a fixed location, even though high CO has been observed soon after the goaf hole starts production, the rapid advance of the face will soon isolate the goaf hole from the O_2 source (ventilation air) behind the longwall face. A general declining trend of CO level as the face moves away from that goaf hole can be anticipated.
- The current CO-based TARP focuses on a single threshold value rather than the trend over a consecutive period. As noted in this analysis, the accumulation of CO normally shows an upward trend given that sufficient O_2-rich environment lasts for a long period. A single record of maximum CO value may rise the concern but should not be treated as the trigger to shut-off the goaf hole. Temporary increase of CO may be caused by a slow-down or

stoppage of the longwall face, and the CO level will decline to an acceptable range once normal face production resumes.

- Once high CO has been detected in a goaf hole, it is useful to examine the CO level in its neighbouring goaf holes since CO release is found to be spatially correlated. A robust diagnosis process be placed underground using a tube-bundle and bag sample monitoring regime rather than using goaf hole gas composition to evacuate the mine for spontaneous combustion risk.

CONCLUSIONS AND RECOMMENDATIONS

This paper analysed gas drainage performance from vertical surface goaf holes in an operating mine with high specific gas emission rates (~20 m^3/t). Field manual monitoring results of daily goaf gas flow rate and gas composition collected from individual goaf holes were analysed. The major challenge of implementing the full potential of goaf drainage system is the perceived risk of sponcom in a goaf using *arbitrary CO trigger set points, without any scientific basis or empirical evidence*. Based on the analysis of extensive dataset from the study mine, this analysis suggests that the following approaches can be taken to maximise goaf hole gas drainage performance without compromising underground sponcom risk management:

- The start-up period and completion period of a longwall panel showed a general trend of CO increase, which indicates the presence of conducive environment for coal oxidation. The deployment and operation strategy of goaf holes in these two periods should be carefully reviewed with specific reference to the use of CO trigger level.
- Optimum control of goaf gas drainage rate based on the distance between the goaf hole and face can be applied, whereby goaf holes are operated in low flow rate when they are close to the face but high flow rates when they are away from the face.
- From an explosion management perspective, the key trigger gases to be monitored are oxygen and methane rather than the use of CO as a trigger to control the goaf hole operation. It is strongly recommended that no goaf holes should be operated at methane concentrations below 30% regardless of the oxygen concentration to foolproof the probability of explosion risks. If there is a consistent presence of O_2 were observed in a number of neighbouring goaf holes, temporary shut-in of these holes should be applied as per the leading practice. Reopening of these holes can only be considered when the face is at least 300 m away from these holes, and their gas composition should be reviewed to ensure the O_2 concentration has dropped to an acceptable level.
- The analyses of data as well as empirical evidence clearly suggested that the use of CO gas as a trigger in goaf hole to identify underground sponcom activity could not be established and use of CO levels based on goaf hole gas composition for mine evacuation is flawed.
- While the investigation into the origin and introduction of CO trigger in TARP could not be established, the paper provides adequate background and the basis to eliminate or revise the use of CO triggers in current surface goaf gas management TARPs. The continued mis-use of CO as a trigger for underground sponcom activity has a detrimental effect on longwall TG gas management for explosion prevention due to early goaf hole termination despite higher levels of methane purity.
- Longwall operations must continue to deploy and monitor underground goaf environment using appropriate tube bundle monitoring and bag sample regime, real-time longwall tailgate airflow and CO monitoring for early indication of sponcom related activities.

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