Longwall Maingate and Tailgate Proactive Sponcom and Gas Management Strategy- An Operational Safety Share on Risk Management

B Belle
Anglo American Steelmaking Coal, Australia; University of New South Wales, Sydney, Australia; University of Queensland, Brisbane, Australia; University of Pretoria, South Africa.

R Balusu
CSIRO Mineral Resources, Australia

ABSTRACT: The evolution of major coal oxidation and resulting sponcom incidents are sudden and may result in catastrophic negative safety outcome or result in the withdrawal of persons and closure of longwall panels/mines. Historically, gassy longwall workings in Australian Goonyella Middle (GM) seam (late-1990's to mid-2010's), experienced increasing trend in CO levels associated with coal oxidation and sponcom indicator gases and major safety incidents were due to oxygen ingress on the maingate side. The original Australian active longwall goaf gas drainage system designs are based on the past work of the CSIRO, supported by the operational experiences. The CSIRO based studies in gassy and hot coal mines had carried out numerical and field data investigations on goaf hole gas flow mechanisms and proactive inertisation strategies for preventative spontaneous combustion and goaf gas management. This critical foundational knowledge work contributed to the original goaf gas drainage and sponcom management strategies in other Australian longwall mines and potentially extended to rest of the world. Considering the risks associated with sponcom, GM seam operations were the first operations in Australia to introduce proactive N2 injection along the MG in mid-to-late-2000's, to manage sponcom fire and explosion risks in an active goaf, despite not having field data readily available to calibrate the models prior to its implementation.

Over two decades ago, active goaf gas drainage flow rates were moderate (2,000 l/s to 3,000 l/s) and the oxygen ingress on TG side was not a major concern. However, with increasing goaf gas drainages rates and manual or automated mode operation of goaf wells to extreme flow rates to address higher longwall goaf gas emissions, TG oxygen ingress and air wash zones became a major issue recently, necessitating the introduction of TG inertisation strategies now to address this emerging issue. Introduction of MG proactive inertisation strategy had ultimately reduced the number of high CO or intensive oxidation incidents over two decades. This paper provides practical safety benefits of longwall tail gate (TG) inertisation supported by the original computational fluid dynamics (CFD) modelling studies carried out by the CSIRO. The field verification with both MG and TG inertisation using proactive N_2 injection during various phases of longwall production and stoppages in an active longwall provides reasonable technical and operational justifications on gas and sponcom management strategy for worker's safety.

1 INTRODUCTION

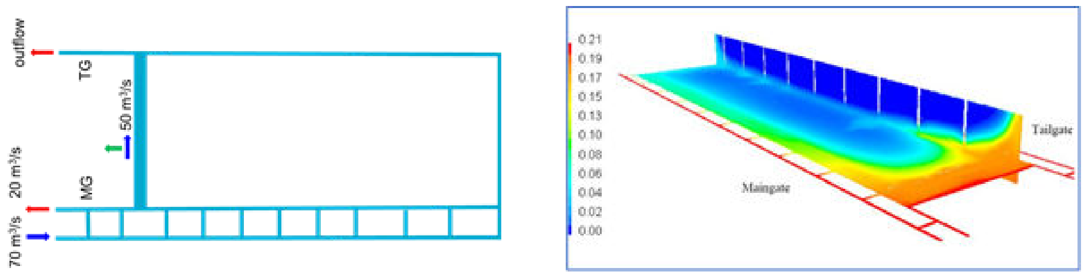
The original and modified longwall seam gas drainage system design evolutions are essentially based on the joint industry led historic initiatives and work of the CSIRO, supported by the GM seam operations (Balusu et al. 2001, 2002, 2004, 2005, 2011, 2017, 2019). The historic review of goaf drainage introduction in Australia and the rest of the world, drainage design and operational practices are summarised elsewhere (Belle, 2015, 2017). In addition, the impact of longwall and TG hole positioning study by the CSIRO for the GM seam operations is summarised elsewhere (Khanal et al, 2021). The science-based CSIRO studies in gassy, sponcom prone hot coal mines had been carried out through numerical and field data investigations on goaf hole gas flow mechanisms and proactive inertisation strategies for preventative spontaneous combustion management. This critical operational knowledge contributed significantly to the original goaf gas drainage and sponcom management strategies in Australian underground longwall mines and potentially extended to rest of the coal mining world. The contradictory nature of the GM seam sponcom led fire and gassy mine requiring maximised goaf drainage capacity systems and the need to reduce oxygen ingress into the MG and TG active goaf required careful operational strategies. The term 'sponcom' used in this paper is used to discuss the various stages of coal oxidation to the development of fully uncontrollable combustion resulting in fire when large quantities of coal left in the goaf due to geo-technical and mining safety considerations. Considering the risks associated with sponcom, GM seam mines were the first operations in Australia to introduce proactive N_2 injection to manage sponcom related fire and explosion risks in active or sealed goaf areas. In this context, it is important to note that inappropriate use of ventilation driven controls for longwall tailgate gas management that are practiced elsewhere in Australia or in the world, are not necessarily apt for gassy, steep geo-thermal gradient and known sponcom prone GM seam mines.

2 BACKGROUND TO GAS AND SPONCOM MANAGEMENT STRATEGIES

Gassy and known sponcom prone GM seam longwall operations require a greater understanding the goaf gas behaviour, post gas drainage control strategies for TG gas management, and well balanced gas and sponcom management strategies of high magnitude gas reservoir mines. Following paragraphs below highlight the spectrum of scientific applied research based engineering controls and monitoring systems developed and improved over the last two decades in the Australian longwall operations.

2.1 *Longwall goaf gas distribution patterns*

In order to provide a visual understanding of goaf gas flow patterns for coal mine workers, operators and ventilation engineers, CFD models of operating longwalls were developed with operating panel geometries of longwall panel (Balusu et al. 2001) covering 1.0 km length of longwall goaf using actual floor contours for 2 gate and 3 gate road development scenarios. A typical longwall schematic with U ventilation system with the total ventilation quantity of 50 m^3/s flows across the longwall face is used in CFD modelling studies are shown in Figure 1.



(a) Typical 2 gate road layout **(b) 3D view of oxygen distribution in the longwall**

Figure 1. Typical 2 gateroad Longwall ventilation system (Balusu, et al. 2002).

At the tailgate (TG) return, an outflow boundary condition was specified in the modelling simulations. The longwall panel width is 300 m and the roadway width on both maingate (MG) and tailgate (TG) sides of the face is 5.4 m. The goaf height up to 80 m above the working seam and the floor strata down to 10 m below the working seam is included in all the CFD models. The CFD models incorporated MG and TG cut-throughs of 5 m in width and cut-throughs spaced at 100 m intervals along the panel and goaf drainage holes replicated the drainage conditions of the operating site. The total number of finite volume cells used for meshing are around 2.0 million, for obtaining the grid independent solutions in simulations.

For visual understanding purposes, methane and oxygen gas distributions patterns in longwall goafs under two different conditions using operational longwall panel gas emissions and goaf gas drainage conditions with total gas emissions into the longwall goaf of around 9,000 l/s with 98% methane (CH_4) is shown Figure 2. The total goaf gas drainage rate was around 8,000 l/s, with gas concentration in different vertical goaf holes varying between 80% and 95% with adjacent sealed panel goaf drainage of 800 l/s for a typical U ventilation system in a 2 gateroad panels. In the methane and oxygen gas distribution color contours below, the red colour indicates higher gas concentration and the blue colour indicates lower methane or oxygen gas concentration. As noted herein, the presence of oxygen and continued methane emissions are contradictory controls requiring finer balance and continued vigilance in goaf drainage operations and highly reliable gas trend monitoring.

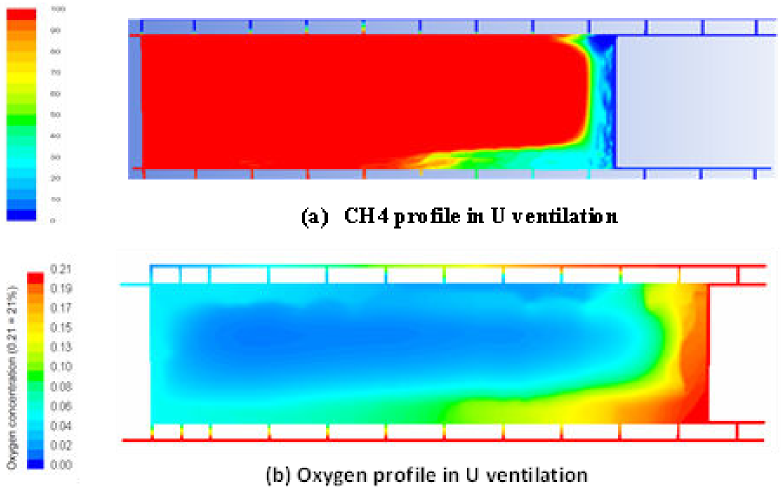


Figure 2. Methane and oxygen gas distributions patterns in longwall goafs under two different conditions.

Various parametric studies by the CSIRO verified by the operational data from Australian mines had indicated that the gradient of the seam, both across the face and along the panel, had a major effect on the distribution of gasses within the goaf. Similarly, results showed that gas emission rate and face airflow have a substantial effect on oxygen ingress into the goaf, particularly into the deep goaf (> 1 to 2 km behind the longwall face). Results show that intake airflow influenced airwash zone in the goaf with over 10% oxygen concentration levels has extended further into the goaf with increase in intake airflow. In base case simulations the high oxygen level zone extended up to 150 - 200 m behind the face, whereas in the case of high intake airflow the high oxygen zone extended up to 300 m into the goaf (Figure 2).

In the recent years, there is often a preferential emphasis put on the “pressure differentials” or loosely termed “pressure” in an active goaf for ventilation and gas management. Historic work in relation to the static pressure distribution in the goaf with traditional practice of gas drainage from two goaf holes near the longwall face is presented visually in Figure 3 for surface goaf holes closest to the face operating at the total flow rate of about 1,500 l/s. Results show that with this type of goaf hole drainage, gas static pressure in the goaf measured at the MG seal builds up to 180 Pa, that is sensitive various other mining and natural factors. The time based static pressure distribution model indicates that all the goaf gas migrates towards the tailgate corner of the goaf and a major proportion of the goaf gas may escape into the tailgate return airway, particularly during low barometric pressure periods. Therefore, both the goaf gas drainage strategy and its operation are paramount in addition to the goaf hole design.

In order to improve the gas drainage system efficiency, deep goaf holes gas drainage strategy was introduced into the modelling simulations. Deep goaf hole drainage in this paper refer to those vertical goaf drainage holes from surface that drain the goaf gas located greater than 1 to 2 km behind the operating longwall face and yet times even near the longwall start up face area for very long panels. The static goaf gas pressure distribution in the goaf with maximized gas drainage strategy is presented in Figure 3. Results showed that the static pressure development in the goaf with this strategy is only 80 Pa, compared with 180 Pa in the traditional strategy scenario. Results indicated that goaf gas migrates to a wider area towards the tailgate side and only a minor proportion of goaf gas escapes towards the tailgate return. In addition, the low goaf gas pressure development in the goaf helps in reducing the effects of changes in barometric pressure on return gas levels. These results indicate that the optimum gas drainage strategy should incorporate goaf holes near the face as well as deep goaf holes with optimized increased numbers in the panel in order to improve the gas drainage system efficiency with large longwall block well retreated with large goaf gas reservoir size.

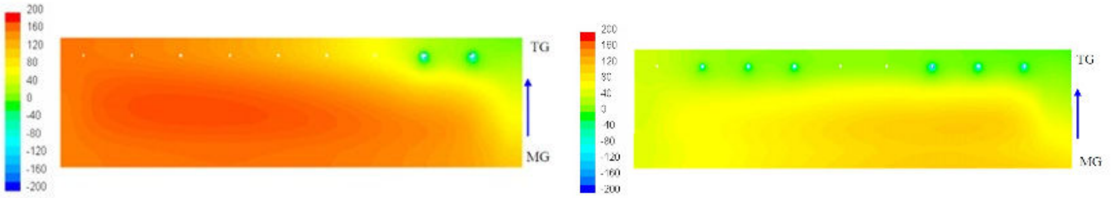


Figure 3. Goaf gas pressure distribution in the goaf with few operating wells behind the face (Left) to maximized goaf drainage system (right).

2.2 *Gas Management Strategies*

As a leading traditional practice, highly gassy mines are to be managed through extensive pre-drainage techniques long before the actual longwall mining to take place. During the active longwall mining, goaf drainage systems are used as the *primary* control for gas management with adequate drainage capacity for maximized drainage along with ventilation as the *secondary* control for gas management as a dilution control (Belle, 2015). Longwall gas emissions have increased significantly in recent years in some Australian longwall mines due to increased seam gas reservoir size with multiple upper and lower seams, higher production rates and increase in mining depths. In addition, there have been mines, previously deployed 3 gateroad systems in their longwall panels for continued access to diesel vehicles during maintenance periods and for gas management. With the greater understanding with extensive and flexible goaf drainage systems and capacity, Australian coal mines use 2 gateroad U ventilation system for longwall panel development and extraction. Extensive scientific and field work has been carried out previously to develop optimum gas and spontaneous combustion control strategies for 2 gateroad longwall panels (Balusu et al. 2001, 2002, 2004, 2005, 2011, 2017, 2019; Belle, 2014, 2015, 2017; Balusu, Belle and Tanguturi, 2017, Balusu and Tanguturi, 2019).

Although 3 gateroad system provides more ventilation capacity during gateroad development and assists in providing more ventilation dilution capacity in tailgate during longwall extraction, its effect on goaf gas distribution and explosive fringe gas profiles in the longwall goaf areas was historically unknown. There is a continued perception that as the 3 gateroad system provides more ventilation capacity for gas dilution in the longwall tailgate return, it would also reduce the explosive fringe gas distribution profile near the tailgate area in the longwall goaf to manage the explosion risk. The results of the CSIRO CFD modelling simulations calibrated with field conditions indicated that there is a significant difference in the spread of explosive fringe gas distribution profiles in the longwall goaf under 2 gateroad and 3 gateroad conditions, i.e. *a significant increase* in the spread of explosive fringe (or close to explosive range) zone in the goaf under 3 gateroad conditions. Based on the results of these investigations, appropriate strategies have been developed for gas control and minimization of the spread of explosive fringe gas distribution in the longwall goaf (Balusu, Belle, Tangutiri, 2021). Therefore, based on the extensive operational gas management experience, it is the pre-drainage and longwall goaf gas drainage management is the primary gas management control rather than ventilation engineering controls to manage the major gas hazard.

One of the major difficulties in the ventilation and gas flow dynamics is our inability to visualize the complex likely gas concentration profiles, i.e., methane or oxygen in the active goaf with time and non-constant retreating longwall. The advances in the CFD numerical calculations have enabled the industry by providing an understanding of gas management or the extent of *'air wash zone'* that is often used colloquially during risk assessment or emergency situations. In this paper, air wash zone is typically referred to as the concentration of relative oxygen in the goaf atmosphere aiding the left over coal oxidation, and typically referred to with oxygen concentration values of 3 % to 21%. Fresh air is the concentration that is representative of longwall fresh air intake. It is to be noted that due to almost no relative airflow movement that can be measured in the goaf may also mean the presence of oxygen even at levels of 2 % to 3 %. The CSIRO studies (Balusu, 2002) provided a visual scenario of potential oxygen distribution in an active LW goaf and goaf well nearer to the LW face. The field studies have noted that (Balusu et al, 2006) the oxygen concentration was above 19 % for up to 100 m behind the longwall face and reduced to 6 % at 250 m behind the face in the absence of any inertisation control. This air penetration distances of 250 m to 350 m may be mainly attributed due to poor MG brattice control practices along with the increased longwall airflow rates for gas dilution purposes and inadequate gas drainage. The tracer gas studies have revealed that the goaf at 300 m behind the face is highly consolidated and does not allow direct travel of air fom the intake side to return side of the TG.

Similarly, methane gas concentration distribution profiles at the tailgate region of different mines vary significantly depending on the geological, gas, mining and operational conditions. Gas concentration distribution profiles (Balusu, 2020) at the tailgate area under three mining conditions are presented in Figure 4. The white box in the plots show the TG motor area and white line replicating the Bretby across the face. In addition, the gas distribution profiles even at the same mine can vary significantly depending on number of conditions, including changes in barometric pressures, goaf falls, gas emission rates, goaf gas drainage efficiency, face location with respect to goaf holes and cut-throughs, face creep, floor contours, caving conditions behind the face and in gateroads, coal production rates, face ventilation, face cutting and chock advance sequences. Gas concentration distribution profiles and potential flammable gas mixture zones near the tailgate roadway area of the longwall face are dynamic and complex in nature and varies widely depending on the changes in above parameters during mining operations. Thus the behavior of goaf gas composition is complex and influenced by mining engineering and fluid dynamics and are to be assessed by suitably skilled, qualified and experienced expert to provide appropriate guidance to safe operation of coal mines.

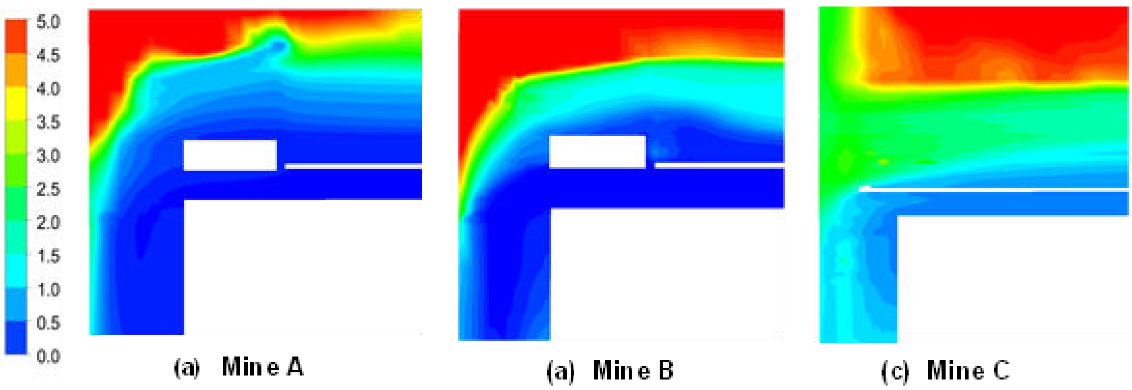


Figure 4. A snapshot of methane gas distributions profiles near the tailgate area of longwalls.

An example comparison of the methane and oxygen gas concentration distribution patterns in the longwall goaf near the tailgate area in a 3 gate longwall retreat scenario are presented in Figure 5. Results of this simulations indicate that the methane gas distribution inbye of the longwall face is close to the explosive range in both cases which reflects the goaf drainage hole design and their operational effectiveness. The contour scale provides the methane and oxygen distribution. For example, 0.207 % equal to 20.7 % oxygen and 0.40% equal to 40 % methane. In the Figure 5, "closed at location 1" signifies the temporary roadway seal. The results of the CFD modelling simulations indicate that there is a significant difference in the spread of explosive fringe gas distribution profiles in the longwall goaf under 2 gateroad and 3 gateroad conditions, i.e. a significant increase in the spread of explosive fringe (or close to explosive range) zone in the goaf under 3 gateroad conditions or partial 3 gate road LW operations.

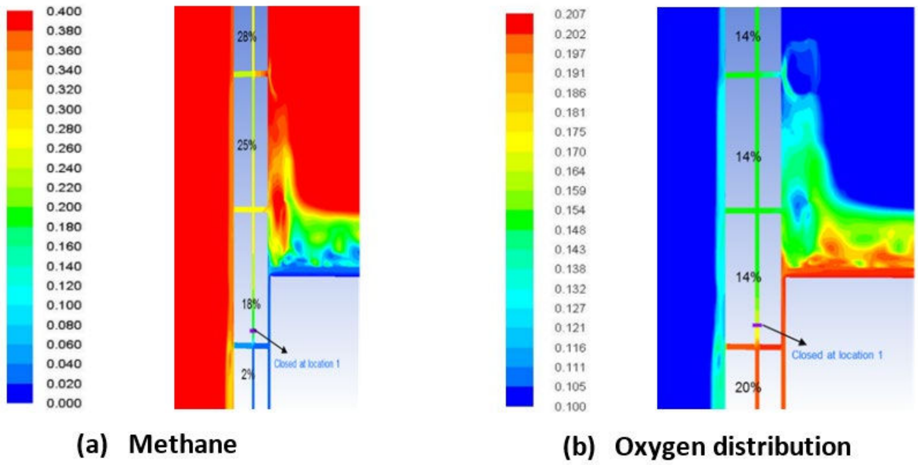


Figure 5. Close up views of methane and oxygen distribution inbye of the longwall face (Balusu, Belle, Tangutiri, 2021).

2.3 *Sponcom management strategies*

Based on the two decades of close collaboration between the coal operators, ACARP and CSIRO, extensive scientific and field-based studies have been carried out. The learning from these studies, have resulted in the following summary and context behind the proactive preventative sponcom and gas management goaf inertisation strategy:

- Major events in Queensland demonstrates the critical importance of proactive sponcom management for underground coal mines extracting/working in known sponcom prone Moranbah region GM seams.
- Widely referred low sponcom propensity (R_{70}) of coal risk ratings in Principal Hazard Management Plan (PHMP) documents and frequency of their testing may be misleading the likely initiation or risk frequency estimations. For example, both German Creek and Goonyella Middle Seam R_{70} values are similar in magnitude but the left-over roof coal in GM seam goaf increase the oxidation risk with increasing depth due to steep geo-thermal gradient.
- Historically, gassy longwall workings in Australian Goonyella Middle (GM) seam (late-1990's to mid-2010's), experienced increasing trend in CO levels associated with coal ox-idation and sponcom indicator gases and major safety incidents were due to oxygen in-gress on the maingate side. To address this issue, MG proactive inertisation strategy was introduced at GM seam operations mid-to-late-2000's, which ultimately reduced the number of high CO incidents over the next decade.
- When MG proactive inertisation strategy developed by the CSIRO and the operators was first introduced, there was no precedence in Australia and there was no field data to val-idate its effectiveness (prior to its implementation). However, it is to be noted that during longwall operations of GM seams, it's the additional proactive N_2 inertisation strategy that was essential to successfully manage the sponcom and resulting major fire risks dur-ing long periods of production stoppages due to geo-technical and mining related matters.
- The evolution of major coal oxidation and sponcom incidents are sudden and may result in catastrophic negative safety outcome or result in the withdrawal of persons and closure of panels/mines.
- In view of the recent incidents in a number of mines working in GM seam (irrespective of the cause of the incidents), elevated oxidation reaction may potentially become an ig-nition source and inadequate control may result in the undesirable safety outcome.

2.4 *Maximised goaf drainage Strategies -Lessons Learned*

To develop optimum and effective goaf gas drainage strategies for any new or operating mine, an extensive goaf gas monitoring scheme should be implemented in at least one or two panels to obtain detailed information on gas flow patterns and goaf gas distribution under various operating circumstances for the site conditions and geometry. In many cases, the recent standard practice of draining gas from 2 to 5 goaf holes near the face operating its peak capacity would not solve the tailgate gas problems, but exacerbate the oxygen ingress into the deeper portion of tailgate area of an active LW goaf. A number of factors including goaf gas emission flow rates and composition, panel ventilation, coal seam gradients, overlying and underlying coal seams, face retreat rates, caving characteristics, and goaf gas flow patterns need to be considered during development of goaf gas drainage strategy and goaf hole operations.

Based on the results of various CSIRO studies and investigations supported by the coal operators over the last two decades, the following practical guidelines are recommended for optimum maximized goaf gas drainage strategies at highly gassy mines:

- Surface goaf holes for gas drainage provide the highest capacity, flexibility and lowest total cost option for goaf gas drainage under most circumstances.
- Goaf holes should be drilled on the return side of the goaf, preferably at 20 to 70 m from gateroad depending on the longwall caving conditions.
- Goaf holes are to be drilled 80 m to 100 m away from faults/dyke areas to overcome coal oxidation and spontaneous combustion risks.
- Uniform, stable and continuous operation of goaf holes are essential for effective longwall ags management (sudden peaks and lows in goaf drainage flow rate increases the coal oxidation potential resulting in sponcom risk).
- Goaf gas drainage hole diameter should be in the range of 250 to 400 mm for optimum flow rates and the goaf holes may be drilled at 50 m to 200 m spacing depending on the longwall gas reservoir size, goaf gas emissions and other mining production conditions.
- The total capacity of the goaf gas drainage plants should be around 2 to 3 times the expected goaf gas emissions to cater for deep goaf holes gas drainage, shifting of goaf plants or goaf hole connection changes and reduced plant efficiencies due to high pressure losses. Provision of a high-capacity and flexible gas drainage system allows optimisation of goaf gas drainage strategies, maximized goaf drainage with retreating longwall, flexibility, improves the overall efficiency and provides greater gas management control on the longwall face.
- The goaf gas drainage system should include a combination of goaf holes near the face and deep goaf holes in the panel in order to improve the overall gas drainage efficiency and to reduce the effects of barometric pressure changes on tailgate gas levels with increasing active goaf gas reservoir size.
- The strategy of continuous operation of deep goaf holes at low to moderate flow rate should be implemented i.e., intermittent operation of deep goaf holes at high capacity may not improve the overall efficiency and may lead to unexpected problems such as oxygen ingress into deep goaf.
- Goaf gas drainage should be carried out from around maximised number of goaf holes with the retreating longwall goaf in the panel (including deep holes), instead of the standard practice of gas drainage from just few goaf holes closest to the face for gassy high production longwall mining.
- Application of increased suction pressure to drain more gas from goaf holes closest to the face might result in increased air dilution, without any net increase in gas drainage flow rates.
- The ventilation system in the panel should be designed to minimise oxygen ingress into the goaf, including immediate sealing-off all the cut-throughs behind the face, MG tight brattice control in order to improve overall gas drainage efficiency.
- Oxygen concentration level in the goaf hole flow should be less than 5% for extended periods of time in goaf holes beyond 100 m from the LW face line to reduce sponcom risk in the longwall goafs during normal production and long periods of stoppages.

- Gas drainage from adjacent old goafs should also be carried out wherever possible, depending on the goaf gas emission flow rates and adjacent seal strengths (Belle, 2014).

3 LW GAS AND PROACTIVE MG AND TG INERTISATION AND MONITORING STRATEGY

In order to manage the elevated oxidation levels with increased goaf gas drainage in high production gassy mines to effectively manage the active longwall TG gas levels, following proactive inertisation strategy was implemented in an operating mine. The optimum locations of the TG and MG holes for both gas and sponcom management with proactive inertisation for high gassy mines were based on the original and fundamental goaf gas and sponcom management work by the CSIRO, calibrated with the operational experiences over the last decade (Balusu, 2021).

3.1 *Data Collation and Limitations*

The study had analysed extensive longwall panel data, that had implemented for the first time, a strategy that incorporated MG and TG nitrogen (97%N_2) inertisation and goaf gas management. The limitations and characteristics of the data used for analyses are summarized briefly below:

1. The goaf drainage hole data which recorded CO, CO_2, CH_4, flow were averaged daily for individual holes collected for the entire longwall panel.
2. Active goaf gas composition was based on the daily individual average goaf hole data comprising, flow, CH_4, O_2, CO, CO_2 composition.
3. Goaf gas flow data with flow rates of > 200 l/s are used in the final analyses, as some of the new goaf holes were usually checked for validating the goaf connections once the longwall had retreated 20 m to 30 m behind the longwall face line.
4. It is to be noted that the data flow rate < 200 l/s is usually associated with the start-up of the goaf hole prior to LW intersections with higher levels of O_2 (> 14%) for short periods.
5. Negative O_2 readings were removed from the data set considering the likely data flaws or sensor measurement errors.
6. It was noted that the data set yet times showed that during the normal operation of goaf wells probably based on TARP trigger levels, resulted in undesirable gas composition mixtures.
7. The data contained over 90 vertical surface goaf drainage holes with a combination of deep goaf, adjacent goaf, MG and TG goaf week operations of the entire longwall panel for effective longwall TG gas management.

3.2 *LW Gas Management and Proactive MG and TG Inertisation Assessment*

An extensive data analyses was carried out for the entire longwall panel for the gas and sponcom management effectiveness and are discussed hereafter. Figure 6 shows the profiles of active longwall goaf gas composition with retreating longwall with likely less than effective inertisation and the absence of TG inertisation.

Key observations from the analyses are as follows:

- The effectiveness of the N_2 injection and the operation of goaf gas flow rate management is reflected in the gas composition of the active longwall goaf gases, viz., CO, O_2, CH_4.
- The composition of higher levels of oxygen behind the longwall face in the TG region (upto 300 m behind the face) may be attributed to the very higher flow rates and goaf holes coming online at the time of goaf formation.
- Similarly, higher daily average CO levels, demonstrate the presence of the excessive and conducive oxygen rich environment as a result of deeper air wash zone in the TG area of the goaf contributing towards early oxidation of left over coal in the goaf.
- It is equally noted that the methane concentration behind the active longwall in overall terms increases in the purity as a result of continued desorption of overlaying undrained coal seams with greater gas reservoir size. The failure to drain the deeper portion of the active longwall goaf will eventually travel towards the tail gate region as a result of

increasing goaf gas reservoir size with the longwall retreat and definitively contributes in higher gas levels during the steep drop in barometric pressures.

- It is equally important to note that the uncontrolled deep goaf hole operation at very high flow rates, may further exacerbate the oxygen rich environment deeper in the TG goaf area in the absence of effective TG inertisation.

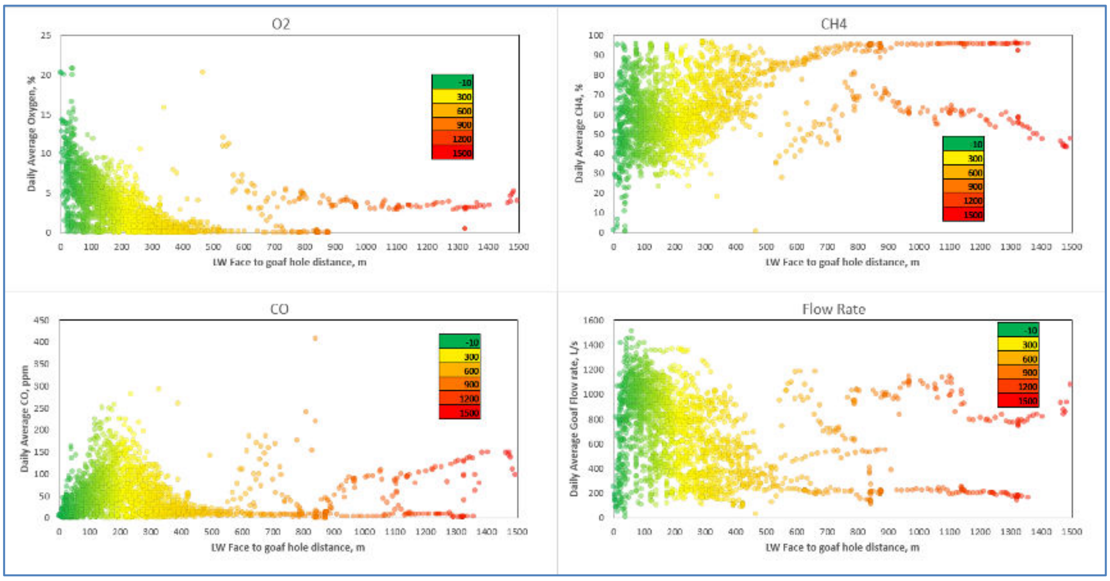


Figure 6. Goaf hole gas composition without the TG inertisation with retreating LW face- Oxygen (Top Left), CH_4 (Top right), CO (Bottom Left); Flow rate (Bottom right).

Similarly, Figure 7 shows the profiles of active longwall goaf gas composition with retreating longwall with effective MG inertisation and with the introduction of TG inertisation for the first time.

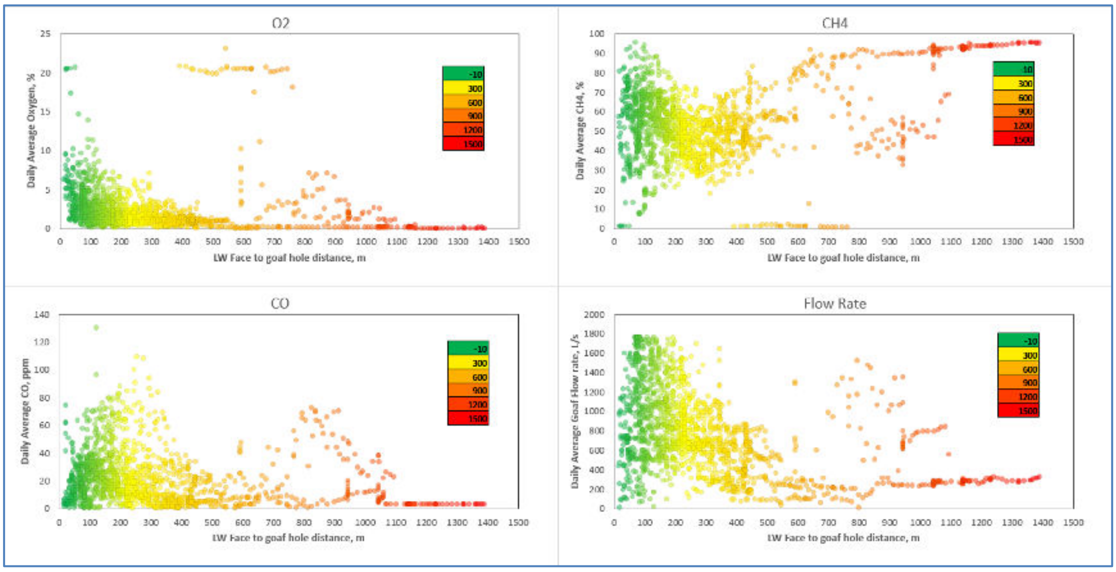


Figure 7. Goaf hole gas composition with MG and TG inertisation with retreating LW face- Oxygen (Top Left), CH_4 (Top right), CO (Bottom Left); Flow rate (Bottom right).

Key observations from the analyses are as follows:

- Combined MG (1500 L/s) and TG inertisation rate of 750 L/s with greater goaf gas management is clearly reflected in the favourable gas composition of the active longwall goaf gases, viz., CO, O2, CH_4.

- The composition of reduced levels of oxygen behind the longwall face in the TG region (upto 100 m behind the LW face) may be attributed to the N_2 injection in the tailgate minimising the oxygen ingress into the goaf. There is a significant difference in the oxygen levels at less than 5 % beyond 100 m of the inbye goaf assisting in minimising the risk of coal oxidation and oxygen presence in the deeper portion of the goaf.
- Similarly, daily average CO levels in the active goaf have significantly reduced, demonstrating the effectiveness of the N_2 injection and less than adequate conducive oxygen presence in the TG airwash zone, thus potentially minimising early oxidation.
- As before, the methane concentration behind the active longwall in overall terms increases in the purity as a result of continued desorption of overlaying undrained coal seams with greater gas reservoir size and aided by the N_2 presence. This environment enables the deeper goaf drainage practices at low to moderate flow rate for maximised goaf gas management and drainage efficiency, to reduce the gas reservoir as well as ventilation air methane (VAM) and greenhouse gas (GHG) management.

3.3 *Discussions of MG and TG inertisation and gas management strategy*

Presence of oxygen in the active goaf is unavoidable when carrying out goaf drainage activities to manage tail gate gas levels of an active longwall. Extensive goaf seal monitoring activities by the industry have provided greater understanding of the goaf dynamics and input to the goaf gas composition studies for over two decades. Figure 8 shows one such historic work that informs the impact of oxygen profile extent as a result of proactive N_2 injection on both TG and MG areas. The reduced air wash zone is clearly evident in the active goaf thus minimising the conducive environment for any elevated oxidation events (Balusu, 2005). Figure 9 provides the latest CSIRO study using calibrated CFD model of MG and TG inertisation strategy for an operating high gassy longwall mine.

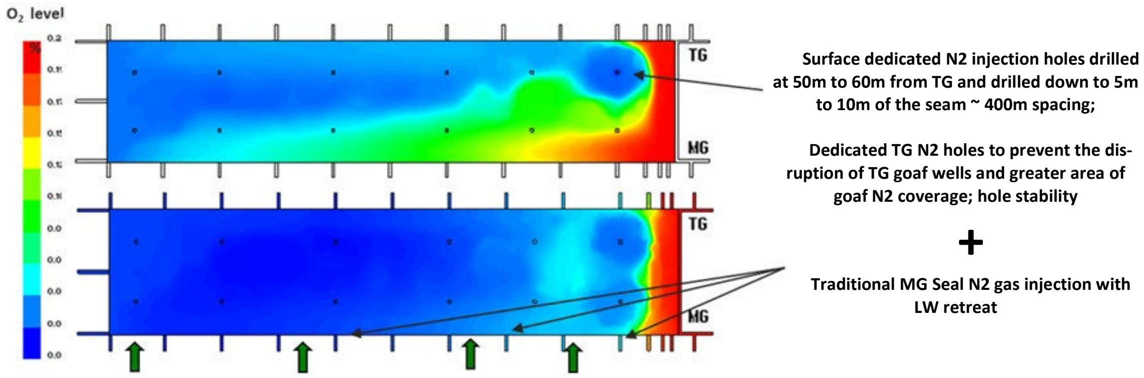


Figure 8. Historic MG and TG inertisation conceptual strategy for longwalls (Balusu, 2005).

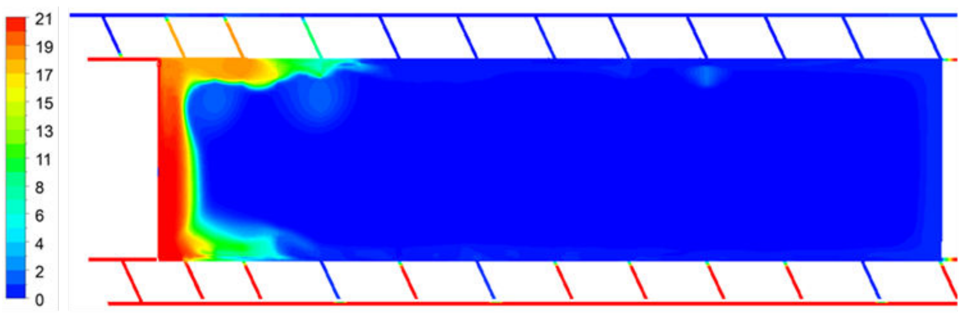


Figure 9. Latest MG and TG inertisation strategy for an operating gassy longwall mine (Balusu, 2021).

Based on the aforementioned gas composition analysis of field goaf hole production data, the goaf gas distribution under intensive gas drainage is summarised as a conceptual model is shown in Figure 10 (Xiang et al, 2021). This drawing may be very subjective—specifically airwash zone contours can shift depending on the complex goaf hole operations for U ventilation system with varying goaf hole operational controls and designs without proactive inertisation. The goaf drainage operation suggests that greater oxidation may be possible in the TG, while there is minimal occurrence of it at MG area with greater ventilation controls such as tight brattice controls and timely build up of seals.

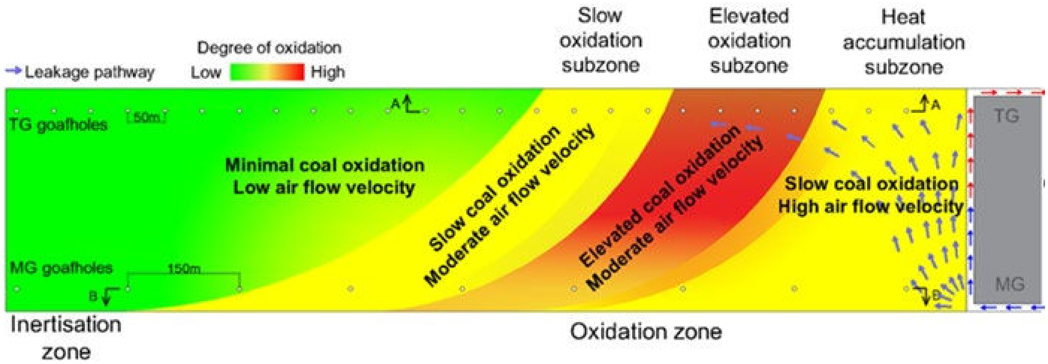


Figure 10. A conceptual model of goaf gas environment under intensive goaf gas drainage impact.

The historic field studies (including tracer gas and goaf hole shut off studies) of CSIRO have shown that reducing and increasing the flow capacity of goaf holes, including complete shut-off of the holes and measuring corresponding changes in return gas levels and response times have shown that 80 % to 90% of goaf gas migrated to longwall return within 1 to 3.0 hrs when goaf holes were 100 to 400 m from the longwall face. Response times varied between two minutes (150 m behind the face) to an hour (1000 m behind the face) along the MG and on the TG goaf holes with few minutes to several hours depending on the goaf hole designs and caving characteristics. Field studies have shown that even when goaf holes located more than 1,000 m from the face, had a substantial effect on gas flow dynamics and on longwall return gas levels. The recommended strategy was that the deep goaf holes are to be operated at low to moderate flow rates continuously as long as the oxygen levels below 3 % and no increased trend in the CO levels.

One of the additional challenges often faced during an unfortunate gas event leads to plethora of suggestions without having appropriate science and data based studies or specialist expertise in the field. One such view is that the goaf drainage flow rate has no impact on oxygen in goaf well or active goaf. Figure 11 below shows the relationship between goaf hole flow rates and goaf hole oxygen levels at various distances from the active longwall face.

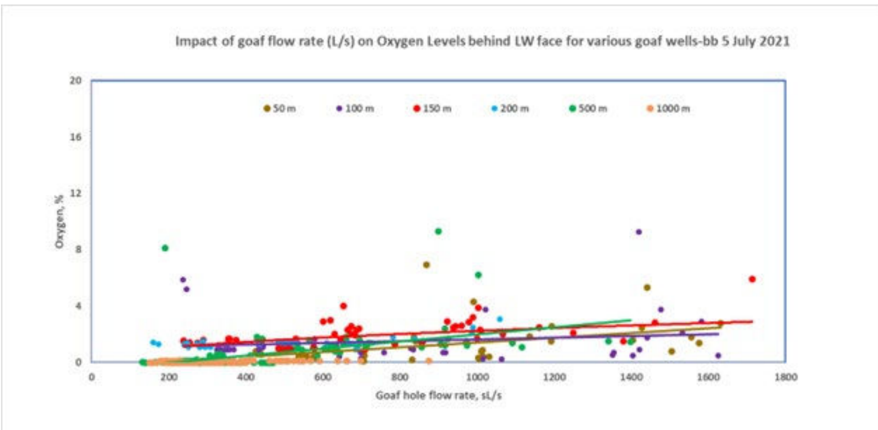


Figure 11. A conceptual model of goaf gas environment under intensive goaf gas drainage impact.

It is observed from the above plot that when the goaf holes are deep, the O_2 levels are typically very low and lower flow rates help to minimize the goaf reservoir size with the retreating longwall with major rate of barometric pressure drop. The general observation is that the increase in goaf flow rate to the extreme regions causes significant increase in the O_2 levels in the goaf, which would require inertisation to minimize the potential oxidation. It's the moderate flow rate with increased number of operating wells against few number of wells operating at extreme flow rates assists in managing the TG gas levels. While the sole intent is to minimize the TG gas levels, the risk of operating few wells at maximum flow rates behind the longwall face would certainly bring the fresh air or oxygen into the active goaf of a retreating longwall. It must be noted that the goaf hole design including its distance from the working seam (historic design of ideally 10 m or 40 ft as in the USA) will have the impact on TG gas levels as well as oxygen levels in the active goaf. Therefore, it's the maximized goaf drainage of active goaf with moderate goaf flow rates and increased number of holes supported by the active inertisation would assist in the effective management of gas and sponcom management risks.

4 CONCLUSIONS AND RECOMMENDATIONS

Conjointly managing the gas and sponcom risk is fundamental to securing a safe underground place of work at GM seam longwall operations. With the increasing gassy and known sponcom prone coal seams and a working depth with steep geothermal gradient is contributing towards the step changes in controls required for gas and sponcom management in order to be compliant with the safe TG gas limits as well as reduced ventilation air methane (VAM) emissions. This strategy reinforces the fundamental importance of the pre-drainage systems with long lead drainage time prior to longwall mining. Over two decades ago in Australia, goaf gas drainage rates in Qld and NSW were low to moderate (1,000 l/s to 3,000 l/s) and the ingress of airwash zone on longwall TG side was not a major concern. However, in the recent years, with increasing goaf gas drainages rates upto 6,000 l/s 10,000 l/s and manual or automatic mode operation of goaf wells to the extreme flow rates to address higher goaf gas emissions, TG oxygen ingressing deeper in the goaf has become a major issue, necessitating the introduction of both TG and MG inertisation strategies now to address this emerging coal oxidation risk. Furthermore, contrary to the views in relation to elevated coal oxidation and sponcom events related to goaf hole spacing and maximized goaf drainage practices, it is prudent to note that there have been historic cases of sponcom events with 400 m to 200 m goaf hole spacing, and even with no goaf drainage practices.

Following safety benefits reasoned with adequate technical and operational justifications for gas and sponcom management strategy aided with both MG and TG inertisation using proactive N2 injection during various phases of longwall production and stoppages:

- In the absence of active and continuous proactive N_2 inertisation, maintaining 5 % to 8 % O_2 levels in the active goaf would be very difficult and may exacerbate the oxidation in an active goaf when the longwall retreat rates slows down or stops for weeks and months. On the contrary, sub optimal goaf drainage to manage the O_2 ingress in deep goaf area of TG region will significantly increase the longwall TG gas levels. This approach would put operations in a dangerous position from gas management perspective.
- Based on the data analyses evidence of manual daily data on O_2, it is noted that there is no clear trend in terms of goaf well spacing justifying the oxygen management, rather the lower O_2 levels in deep goaf or when the LW face is further away from the goaf well, are conducive to operate at lower flow rates for steady deeper goaf drainage holes for gas management for retreating longwall of growing goaf gas reservoir size.
- It is the operational management of goaf wells (not sudden or automatic operation of the goaf wells to the extreme flow rates, rather stepwise increase) with proactive LW active goaf inertisation for sponcom management will enable the appropriate maximised goaf drainage gas management to manage the longwall return gas levels and oxidation risks.
- The introduction of TG inertisation assists in reducing the airwash zone. In addition, longwall operations need to continue with the leapfrogging of well-established MG seal inertisation strategy [including quicker and timely MG seal build, and tight MG brattice

control], along with the dedicated tube bundle monitoring points for goaf gas monitoring to understand the goaf flow dynamics and sponcom management.

- As a general long-term strategy, known sponcom prone longwall operations to ensure flexible and contingency inertisation infrastructure is readily available and to remain in a state that it is able to be recommissioned within a single shift at any time during the monitoring period.
- The association of slow retreat due to known or unknown geological structures in the longwall hazard plan and known historic oxidation related incidents, have further reinforced the active inertisation system maintaining at least 2,200 l/s of inert flow into the active panel [around 1200 l/s on the MG side and 1000 l/s on the TG side using dedicated vertical N_2 holes drilled 5 to 10 m from the working seam height].
- Considering the various uncertainties associated with the LW operations in sponcom prone seams, recommendation of inertisation holes at 200 m spacing on TG side is essential and appropriate for long term risk management planning and design purposes. If the evidence suggests otherwise, i.e., constant increased retreat or no stoppages, then TG proactive inertisation may be carried out through inertisation holes at increased spacing (i.e. alternate inertisation holes) in those areas. This would mean that the intermediate dedicated holes and other old/deep inertisation holes can be equally used for oxygen ingress or airwash zone monitoring and sponcom monitoring on the TG side of the goaf as per the oxygen limit recommendations of an active goaf.
- It is to be noted that these gas and sponcom management strategies are not merely based on the LW retreat rate, but also includes the inherent nature of seam propensity for sponcom despite it being equally rated as “low” risk sometimes, geo-thermal gradient, existence of faults and structures, amount of coal left behind, changes to the goaf hole designs, delay in operational related building of MG seals, inadequate MG brattice leakage control for long periods. other engineering related uncertainties associated with the LW equipment, strata control uncertainties associated with moisture/water in TG roadways, and uncertainties associated with cavity control measures.
- The implemented TG and MG proactive N_2 inertisation strategy of active longwall goaf at the sponcom prone seam has resulted in the new technical/empirical data generation in verifying the fundamental understanding of goaf gas drainage maximization and sponcom management.
- Finally, strengthening the proactive inertisation strategy on both MG and TG with flexible inertisation capacity and responding to the up to date trigger response values of the oxidation scenario rapidly developing into an advanced stage using appropriate early monitoring strategy is essential for the future proofing of underground sponcom risk.

5 REFERENCES

Balusu, R., Deguchi, G., Holland, R., Moreby, R., Xue, S., Wendt, M. & Mallett, C. (2001). Goaf gas flow mechanics and development of gas and sponcom control strategies at a highly gassy coal mine. Australia-Japan Technology Exchange Workshop, 3-4, December 2001. Hunter Valley, Australia. 18 pp.

Balusu R, Mallett C, Xue S, Wendt M, and Worrall R (2002). Mine Gas Control – JCOAL, CSIRO and Dartbrook Collaborative project Final report. CSIRO Exploration and Mining Report No. 1012C, March/October 2002, 183pp.

Balusu, R., Tuffs, N., Peace, R., Harvey, T., Xue, S., Ishikawa, H. (2004). Optimisation of Goaf Gas Drainage and Contro Strategies, ACARP Project C10017, CSIRO Exploration and Mining Report 1186F, 149 pp.

Rao Balusu, Ting X Ren and Patrick Humphries,(2005). Proactive Inertisation Strategies and Technology Development, ACARP Project C12020, CSIRO Exploration and Mining Report P2006/26, 114 pp.

Balusu, R., Schiefelbein, K., Ren, T, O’Grady, P, Harvey T. (2011). Prevention and control of fires and explosions in underground coal mines, The Australian Mine Ventilation Conference, Sydney, Australia, September 2011, pp 69-77.

Balusu, R., Belle, B., Tanguturi, K. (2017). Development of gas and spontaneous combustion control strategies for 6.0km long longwall panels, 16th US Mine Ventilation Symposium, Golden, Colorado, USA, June 2017, pp 18-11 – 18-18.

Balusu, R., Belle, B., Tanguturi, K. (2019). Development of Goaf Gas Drainage and Inertisation Strategies in 1.0-km- and 3.0km-Long Panels. Mining, Metallurgy and Exploration. 2019; 36(6):1127-1136. https://doi.org/10.1007/s42461-019-0071-9

Balusu, R., Tanguturi, K. (2019). Gas management and risk mitigation strategies for longwalls, ACARP Project C25066, CSIRO Energy Report EP191657, March 2019, 210 pp.

Balusu, R, Tanguturi, K, Belle, B. (2021). Goaf gas distribution profiles near the longwall tailgate area, , Proceedings of the 18th North American Mine Ventilation Symposium, 12-17 June, 2021, Rapid City, South Dakota, USA, Edited ByPurushotham Tukkaraja.

Balusu, R. (2020). Longwall Tailgate Gas Compositions, Internal Industry Note, Australia

Balusu, R. (2021). Unpublished CFD Model Study on MG and TG inertisation Strategies, CSIRO.

Belle, B, 2014. Evaluation of barometric pressure and cage effect on longwall tailgate gas levels for prevention of explosion in coalmines, IMVC, Johannesburg.

Belle, B. (2015). Innovative tailgate mobile goaf gas management in two gateroad longwall panels – concept to implementation", The Australian Mine Ventilation Conference, Sydney, Australia.

Belle, B. (2017). Optimal goaf hole spacing in high production gassy Australian longwall mines – operational experiences, The Australian Mine Ventilation Conference, Brisbane, Australia.

Khanal, M, Poulsen, B, Adhikary, D, Balusu, R, Wilkins, A, Belle, B. (2021). Numerical Study of Stability and Connectivity of Vertical Goaf Drainage Holes. Geotechnical and Geological Engineering. 2021; 39(3):2669-2679. https://doi.org/10.1007/s10706-020-01650-6.

Xiang, Z, Si, G, Wang, Y, Belle, B, Webb D. (2021). Goaf gas drainage and its impact on coal oxidation behaviour: A conceptual model, International Journal of Coal Geology, Volume 248, 103878.