Queensland Coal Mining Board of Inquiry

Responses to the Questions from the Board of Inquiry

Dr Rao Balusu

November 2020

Scope:

The author provides this independent expert opinion in response to questions provided by the Queensland Coal Mining Board of Inquiry (the **Board of Inquiry**) on 11 September 2020 (set out below) (the **Questions**) based on:

a) information provided by the Board of Inquiry; and/or
b) publicly available information,

and is restricted to his expert knowledge in the area of management of gas and oxygen in goafs. The author has not undertaken any scientific research in answering the Questions.

For the avoidance of doubt, this document and the responses contained herein are limited to the Questions only and do not address any of the incidents the subject of the Board of Inquiry.

This document and the responses contained herein may only be used for the internal purposes of the Board of Inquiry.

The author is bound by the policies and procedures of his employer in providing this opinion.

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Questions for Dr Rao Balusu

1. Any comments/update on the ACARP Report C15020:- Foam Injection Technologies for Goaf Inertisation.
2. Any knowledge of other methods employed overseas to prevent air ingress into the active goaf at the maingate and tailgate ends of a retreating longwall face?
3. Any knowledge or comments in relation to goaf management practices in Poland as described in the paper – Szlazak, N., Obracaj, D., Swolkein, J., 2020, *Enhancing Safety in the Polish High Methane Mines: an Overview*. In particular comments on figure 2 on page 575 with the seals made of chemical agents.
4. Any comments (including practical implementation) from the paper by Ren, T. X., Balusu, R., 2009, *Proactive goaf inertisation for controlling longwall goaf heatings,* The 6th International Conference on Mining Science & Technology.
5. Any other knowledge in relation to overseas experience with active goaf inertisation?
6. Any knowledge or comments in relation to active goaf inertisation strategies as were practiced at the Yancoal - Austar Mine in NSW?
7. The role of pressure chambers incorporated into goaf seals (as practiced at Austar) in regard to active goaf inertisation?
8. Any thoughts on the required delivery capacity of inert gas generators to implement active goaf inertisation and in particular against production rates?
9. Recommendations on the preferred gas for inertisation (N2 versus CO2)?
10. The impact that proactive inertisation may have on traditional spontaneous combustion indicators and what would be the recommended indicators to use in conjunction with active goaf inertisation?
11. Any thoughts on how to manage goaf drainage in combination with active goaf inertisation?
12. Recommended practices in terms of ventilation pressures over goaf seals and around goafs?
13. Any comments you believe should be made in the management of active goafs in gassy mines?

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Structure of responses to questions:

For each question, the response is presented in two parts. First, background information related to outcomes of previous research projects and literature review into the topics raised and knowledge of operational experience in Australian and overseas mines is presented. This is followed by a list of specific comments and opinions as requested by each question.

Acknowledgments:

The author expresses his gratitude and appreciation to all the authors of the papers referenced in this document. Figures have not been reproduced in this document, instead a reference to the figure as it appears in the relevant source is provided.

Question (1): Any comments/update on the ACARP Report C15020: Foam Injection Technologies for Goaf Inertisation?

Q(1): Background Information:

Foam technology has been used for the prevention and control of spontaneous combustion in underground mines in various countries over the years with mixed results [References 2, 32]. Different types of foams and/or variations of their chemical compositions have been developed and trialled in goafs, particularly in slowly retreating longwall panels. Foam technology was also used in Australia for control of heatings/fires at mine sites from the late 1990's, which involved foam injection through surface boreholes into the goaf over the heating areas. The standard foam used for fire control operations has a very short life/stability of a few hours and needs to be injected continuously over the heating area or at nearby locations to improve the effectiveness of inertisation. Fire control operations may last from a few days to weeks, and it is feasible to prepare and inject foam continuously over that short period. The objective of using high expansion foam technology in 'active goafs' is to minimise oxygen ingress into the goaf and to improve the efficiency of nitrogen inertisation. To achieve this objective, i.e. for foam application as a routine operation at mine sites, foam stability needs to be increased significantly, from a few hours to a few weeks, for its practical implementation.

CSIRO in collaboration with the mining industry carried out the above mentioned ACARP project C15020 [30] to investigate the feasibility of foam application in underground coal mines with the aim of improving the effectiveness of proactive inertisation. Laboratory studies during the project indicated that foam produced through a blend of a standard foaming surfactant, a foam-stabilising surfactant and a rheology-modifier for the water can last up to a week. Foam trials at mine sites along with tracer gas studies indicated that the introduction of a high expansion foam plug into the collapsed gateroads behind the longwall face could potentially increase the effectiveness of proactive inertisation. However, during field trials it was found that the foam could last only a few hours due to high air velocity and other underground mining conditions. In addition, the height to which foam built up in the collapsed gateroad and adjacent goaf area was not apparent.

Q(1): Comments and Opinions:

- After ACARP project C15020, CSIRO has not carried out any further studies on foam technology [30].
- It is not practicable to introduce high expansion foam, uninterrupted, into active goafs as a reliable preventative control measure during normal longwall operations, particularly when it needs to be effective continuously (24/7, 365 days) under high retreat rates.
- Although foam technology may not be practicable as a preventative measure, it is still useful for heating/fire control operations and may need to be used strategically.
- It is recommended to further develop foam technology for application in heating control operations and to resolve any operational issues. The foam generation equipment, foaming compounds required, and foam pumping systems for foam injection through the surface boreholes may be made available at Mines Rescue Stations for its potential applications.
- Foam technology may also be used in longwall panels in high-risk situations, such as during expected long duration longwall stoppages, and if required during longwall take off periods near the finish line. Application of foam technology in these situations has the potential to contribute to increased inertisation in the close by sections of the goaf behind the longwall face and may assist in minimising the risk of spontaneous combustion.

Question (2): Any Knowledge of other methods employed overseas to prevent air ingress into the active goaf at the maingate and tailgate ends of a retreating longwall face?

Q(2): Background Information:

A number of methods and technologies have been attempted in several coal producing countries to minimise oxygen ingress into the longwall goaf areas. These methods include:

- Packing off the collapsed gateroads on both sides of the goaf at suitable intervals with bag walls and gate side packs [Fig 1 of reference 31];
- Building walls behind the retreating face at every cut-through junction [Fig 4 of 49];
- Creating a pressure chamber between two bags/walls inbye of the face, and injecting air or nitrogen into the pressure chamber [Fig 1 of 31, Fig 4 of 49];
- Using fly-ash or slurry in combination with foam or three-phase foam injection into the goaf through pre-perforated tubes or boreholes [32];
- Constructing seals made of chemical agents or quick-setting agents/ foaming concrete at every cut-through behind the retreating longwall face [43, 44];
- Building a fly ash wall every 20m and a brattice curtain every 5m in both gateroads behind the retreating longwall [50];
- Implementing a tailgate back-return ventilation system with two predeveloped tailgate gateroads (3 gateroads systems); or developing a second tailgate with packed walls and construction of seals at every cut-through to isolate the goaf [Figs 4 & 2 of 37]; and
- Employing proactive inertisation, i.e. injection of nitrogen into the goaf, with and without foam or other sealing techniques [1, 2, 3, 23, 29, 35, 38, 44, 45, 46, 50, 51, 52].

A review of the literature indicates that trials of sealing collapsed gateroads behind the retreating face were not successful in stopping the ingress of air into the active goaf. It is to be noted that a number of spontaneous combustion/ heating incidents have occurred in those mines over the years. An attempt was made in Australia also in the late 1990's to seal off the collapsed gateroad behind the longwall face by pumping foaming concrete from underground workings, but this was not successful. It is to be noted here that back-return ventilation systems with two tailgate gateroads (3 gateroad development) configurations were developed mostly to manage gas at the tailgate corner of the face rather than for prevention of oxygen ingress into the longwall goaf.

A literature review indicates that nitrogen injection is being used extensively in several coal mining countries around the world for both fire control operations as well as for minimising oxygen ingress into the goaf areas to manage spontaneous combustion. Comments and opinion on the inertisation strategy are presented in responses to Questions 4 & 5.

Q(2): Comments and Opinions:

- Most of the sealing methods discussed above were used/trialled on longwall faces with very slow retreat rates and significantly lower production levels when compared with current production rates in Australian longwalls. It would be impractical to adopt any of these sealing methods in active goafs of modern-day fast retreating longwalls with production levels of around 5-10 million tonnes (MT) per year.
- It is not practicable to completely seal off the collapsed gateroads in the active goaf behind the retreating longwall face. Although seals constructed behind the face in collapsed gateroads would provide some resistance to air ingress into the longwall goafs, they would not

be able to completely stop air or oxygen ingress into the active goaf, unless supplemented by proactive inertisation in the inbye deep sections of the goaf.

- The goaf caving zone/ high permeability region around the collapsed gateroads can reach up to 15-20m height above the floor level and a high permeability region can extend up to 20-40m wide into the goaf from the pillar rib-lines. Goaf seals constructed behind the retreating face will not be able to completely seal off such a high permeability region around the sides of the active goaf.
- Remote sealing of collapsed gateroads with foaming concrete or fly ash may be used under high-risk scenarios, such as during expected long duration longwall stoppages at locations outbye of the fault areas, and if required under flat seam gradient conditions in highly spontaneous combustion prone mines to improve the effectiveness of proactive inertisation. More research and investigations need to be carried out in this area.

Question (3): Any Knowledge or comments in relation to goaf management practices in Poland as described in the paper – Szlazak, N., Obracaj, D., Swolkein, J., 2020, Enhancing Safety in the Polish High Methane Mines: an Overview. In particular comments on figure 2 on page 575 with seals made of chemical agents?

Q(3): Background Information:

Szlazak et al, 2020 [43] presents a review of methane gas conditions and ventilation systems used in Polish mines for longwall gas management. The U type ventilation system with parallel return roadway (3 gateroad system), sometimes known as a 'tailgate back return system' is used in highly gassy mines [43, 44]. The typical localisation of additional ventilation devices along with seals for tailgate gas management are shown in Fig 2, page 575 of [43].

The paper mentions that the total number of longwall panels in highly gassy mines varies from a few panels to even a dozen longwall panels, to achieve required total mine production levels. Review of the paper indicates that the Polish mining industry uses only underground post-drainage methods, such as cross-measure holes drainage systems due to deeper mining conditions. The average methane drainage efficiency is reported to be approximately 40% in mines with a U ventilation system. Therefore, even in medium gassy mining conditions, such as around 3,000 l/s of goaf gas emissions, it is necessary to use additional control measures at the tailgate for gas management.

The tailgate configuration presented in Fig 2 of [43] shows that Polish mines employ a combination of ventilation strategies to manage goaf gas at the tailgate corner of the face, including a tailgate back-return system, wing curtains, air movers, forcing fans with ducting, etc in combination with seals made of chemical and quick setting agents behind the longwall face.

Q(3): Comments and Opinions:

- The highly complex ventilation configuration and control measures presented in Fig 2 of [43] seems to have been developed primarily to manage gas at the tailgate corner, not for reducing oxygen ingress into the goaf. This arrangement may allow gas management at the tailgate area but does not address the fundamental issue of high gas migration to the longwall return.
- It is time consuming and may not be practicable to build seals as shown in Fig 2 of [43] under Australian mining conditions with a single tailgate gateroad and fast retreating rates for high production levels of around 5-10 MT per year. In general, the production levels per longwall

face under Polish conditions are substantially lower when compared with production levels in Australia.

- Even if two tailgate gateroads are used (with a 3 gateroad system), it is not practicable to completely seal off the tailgate roadway in the goaf just behind the fast retreating longwall face, as discussed in the following point.
- In Australia, depending on individual mine conditions, the tailgate corner area behind the longwall face is largely open up to 15-30m deep behind the face due to high support density and cable bolts used in the gateroads. The open area just behind the face at the tailgate gateroad corner may reach up to 10-15m in height and may also extend up to 10-15m wide into the goaf from the barrier rib-line, depending on site specific conditions. Even if it is assumed that it is feasible to build some sort of seals using remote sealing methods from the surface, these seals would not be able to seal the immediate goaf area behind the face completely and would not stop gas migration towards the tailgate return roadway.
- Although two tailgate gateroads (i.e. a 3 gateroad system) would allow a 'tailgate back-return ventilation system' to address the tailgate gas issue, it presents its own problems including expansion of the explosive fringe gas distribution area into the second open gateroad behind the longwall face.
- In Australian mines, 'wing curtains' colloquially known as 'sherwood curtains' are used in the tailgate roadway to divert the goaf gas stream towards the barrier pillar rib side of the tailgate corner to assist in managing gas levels at the tailgate drive motor area.
- Attempts to dilute methane gas concentration at the tailgate corner with the help of air blowers or similar techniques may assist in diverting the gas away from the tailgate drive motor area, but do not address the fundamental issues of goaf gas drainage or high methane gas migration into the longwall tailgate return roadway.
- Attempts to stop tailgate goaf gas migration towards the longwall return without sufficient/ high capacity goaf gas drainage systems may result in accumulation/build-up of methane in the goaf and may present its own unexpected problems during barometric pressure variation periods or during goaf falls.

Question (4): Any comments (including practical implementation) from the paper by Ren, T.X., Balusu, R., 2009, Proactive goaf inertisation for controlling longwall goaf heatings, The 6th International Conference on Mining Science & Technology?

Q(4): Background Information:

Initial inertisation projects in Queensland involved development and field testing of low-flow and high-flow inert gas generators at mine sites to inertise large goaf areas [20]. Later, inertisation research in Australia focussed on developing optimum strategies for achieving effective goaf inertisation within a few hours of sealing the panel. These optimum strategies have been demonstrated successfully at mine sites [15, 16] and are being used regularly during panel sealing operations [26]. A critical review of overseas inertisation applications and Australian heating incidents and control operations has indicated that the success or failure of inertisation operations depends entirely on the design and implementation of appropriate inertisation strategies to suit local mining conditions.

CSIRO in collaboration with the mining industry has carried out the ACARP research program [39] referred to in this question, to develop and demonstrate effective proactive inertisation strategies to reduce oxygen ingress into active goaf areas in order to minimise the risk of spontaneous combustion.

The ACARP research integrated extensive field studies and computational fluid dynamics (CFD) models of goaf gas flow to develop proactive inertisation strategies to reduce oxygen ingress into goaf areas. Extensive modelling studies were carried out under different mining conditions and seam gradients to investigate the effect of various proactive inertisation strategies on oxygen ingress patterns into the goaf. The inertisation studies included inert gas injection through cut-throughs and boreholes at different locations behind the face, different inert gases, various inert gas flow rates, and different inertisation strategies with single point or multi point inert gas injection. The research has developed a fundamental understanding of gas flow mechanics in longwall goafs and has provided a detailed understanding of the effect of various inertisation strategies on oxygen ingress patterns in the longwall goafs [Fig 5 of 10]. The results of this research are presented in various reports and papers [7, 10, 11, 12] as well as in [39], referred to in this question. The proactive inertisation strategies developed during the research have been implemented at mine sites in collaboration with the industry, and the results of one such field study are presented in Fig 7 of [10], showing gas distribution in the goaf before and after inert gas injection. These results show that the proactive inertisation strategy was highly successful in reducing oxygen ingress into the active goaf. These proactive inertisation strategies have been fine-tuned over the years to suit changing mining conditions such as longer panels, flat seam gradients and very high production rates [5].

Q(4): Comments and Opinions:

- It is practicable to implement the recommended proactive inertisation strategies in current high production longwall panels as a routine and continuous practice.
- As shown in Fig 5a of [10], oxygen ingress into the goaf on the maingate intake side would be very high when compared with oxygen ingress on tailgate side in general. This is due to high kinetic energy/ momentum of the intake airflow and lower elevation of the maingate roadway in general. Of course, oxygen ingress on the tailgate side depends on goaf gas drainage flow rates and the goaf gas drainage strategy.
- Inertisation modelling studies indicated that inert gas injection within 30-50m behind the longwall face would not be effective in reducing oxygen ingress into the active goaf [11]. It is to be noted here that even in small area blind heading auger holes, building a shroud and injecting inert gas at the collar were found to be ineffective and air dilution occurred up to 50m into the auger hole. Injection of inert gas at the auger cutting head, i.e. at the inbye deep location, provided the best results for inertising the cutting head atmosphere [47].
- Preliminary studies indicated that inert gas injection through surface boreholes located more than 100m behind the face and 40-50m into the goaf from the gateroads at strategic locations along the panel would assist in minimising oxygen ingress into the goaf area [11, 39]. However, as longwall panels in general will not have any surface boreholes on the maingate side (although recently a few surface MG boreholes have been drilled), research so far has concentrated on developing appropriate strategies for inert gas injection through maingate cut-through seals to facilitate practical implementation of the proactive inertisation strategy as a continuous practice in longwall retreat operations.
- Studies have indicated that inert gas should be injected at more than 200m behind the face through maingate cut-through seals at multiple strategic points for minimising oxygen ingress into the active goafs. Some of the inert gas injection locations should be moved forward with

the face retreat and some injection points to be located at the face start-up area. Other strategic locations need to be maintained with continuous inert gas injection.

- Proactive inertisation in the longwall goaf involving injection of inert gas directly into the goaf at strategic deep locations, i.e. at the inbye locations, at high flow rates would be an effective and practical strategy under normal longwall retreat operations.
- It is also recommended that maingate curtains be installed between the first chock and the rib to reduce intake airflow ingress into the active goaf. It is also recommended that this curtain be extended to cover the first 3-5 chocks to further reduce intake air ingress into the active goaf. Studies indicated that maingate curtains would assist in significantly reducing oxygen ingress into the goaf and also assist in improving the effectiveness of proactive inertisation.
- In the early 2000's, a minimum inert gas flow rate of 500 l/s was recommended based on production rates and mining conditions at that time. After the initial project, research continued to further refine and update the proactive inertisation strategies for high production longwall mines with faster retreat rates and for mines under flat seam gradients. In the current mining environment with longer panels, high production rates and high goaf gas drainage requirements, substantially higher inert gas flow rates of around 1,500 l/s to 2,000 l/s into the goaf are required, as discussed in response to Question 8.
- In addition to providing adequate inert gas plant capacity at the mine site, it is also critical to continuously monitor actual inert gas flow rates at various injection points to ensure planned inert gas injection and effective inertisation in active goafs have been achieved.
- Fundamental understanding of goaf gas flow mechanics and design of inertisation strategies to suit the specific mining conditions are keys to successful active goaf inertisation.
- Further research is recommended to advance proactive inertisation technology/strategies including investigation of the effect of inert gas injection through surface boreholes into the goaf at different locations on both maingate and tailgate sides, in addition to the current practice of injecting inert gas through the maingate cut-through seals.
- Proactive inertisation with continuous inert gas injection into the deep goaf is highly recommended as a practical strategy for prevention and control of spontaneous combustion in active longwall goafs.

Question (5): Any Knowledge in relation to overseas experience with active goaf inertisation?

Q(5): Background Information:

A literature review indicates that inertisation technology is being used extensively in a number of coal mining countries around the world for both fire control operations as well as for minimising oxygen ingress into the longwall active goaf areas to manage spontaneous combustion [1, 2, 3, 23, 29, 31, 38, 45, 46, 49, 50, 52]. Proactive inertisation technology has also been used successfully in bord and pillar extraction panels [7, 35, 51]. Gas flow patterns in a goaf are complex, as many factors such as ventilation pressure differentials, gas densities, buoyancy, seam gradients, goaf drainage and caving characteristics are involved. A critical review of these overseas applications indicated that development of appropriate inertisation strategies to suit local mining conditions is critical in achieving effective inertisation in active goaf areas.

In some overseas countries, nitrogen is injected into the active goaf through pipes progressively deployed in the goaf from the maingate during longwall retreat or from boreholes distributed in the caved area or through boreholes drilled in the barrier pillars. A review of overseas goaf inertisation studies indicated that nitrogen injection should be done with a minimum flowrate and at a minimum distance behind the face so that nitrogen is not diluted 'at source' by the air in the nearby goaf. Overseas studies indicated that even in longwall faces with only 35 m^3/s airflow, inert gas needs to be injected at 100m behind the face for efficient inertisation. Analysis of samples obtained from the goaf indicated that the injected nitrogen replaces oxygen as well as methane, resulting in a safer atmosphere in the goaf.

The results of field studies in bord and pillar extraction panels [7, 35, 51] also indicated that even under very limited intake airflow rates of 15 m^3/s, inert gas injection close to the intake roadway would not be effective in achieving goaf inertisation. These studies indicated that inert gas injection at inbye locations deep in the goaf would be far more effective than inert gas injection close to the intake roadway. The results of the field studies have shown that the proactive technologies and strategies adopted are successful in preventing fires at the field sites.

Q(5): Comments and Opinions:

- Overseas experience with active goaf inertisation in the 20th century produced mixed results. In general, the traditional inertisation practice of injecting inert gas just behind the face has not been successful. Along with inert gas injection into the goaf, other control measures such as foam injection, fly ash injection, building of walls, inert gas injection into balance chambers, etc in the collapsed gateroads behind the face have also been trialled at several mines with mixed success rates in increasing the effectiveness of goaf inertisation.
- Longwalls panels in some overseas mines are developed using a single gateroad system with no cut-through connections between the panels. In those panels, a steel wire-reinforced pipe is left buried in the collapsed maingate intake roadway every 50m of face retreat and inert gas pumped into that pipe continuously, aiming to inject inert gas at around 50m behind the face. In some cases, fly-ash is also injected at every 20m retreat to build-up a partial wall in the collapsed roadway to improve the efficiency of proactive inertisation.
- Spontaneous combustion management in goaf areas requires implementation of control measures on a continuous basis and should cover the entire highly permeable goaf area. It is not practicable to cover the entire porous region of the goaf with traditional sealing methods such as injecting fly ash or chemical gels over the collapsed goaf in fast retreating longwall panels.
- With improved understanding of goaf gas flow mechanics in recent decades, significant improvements have been made to proactive inertisation strategies involving inert gas injection at higher flow rates into the deeper sections of the goaf with successful results.
- The main advantage of the inertisation technology is that it can be implemented successfully in the field with little interference to mining operations and on a continuous basis.
- Nitrogen injection is being used extensively in several coal mining countries around the world for both fire control operations as well as for minimising oxygen ingress into the active goaf areas to manage spontaneous combustion.

Question (6): Any Knowledge or comments in relation to active goaf inertisation strategies as were practiced at the Yancoal – Austar Mine in NSW?

Q(6): Background Information:

Maintaining an inert atmosphere in sealed-off goaf areas has been a major challenge, particularly in fire affected 'sealed goafs'. A number of seals around the sealed goafs can exhibit 'breathe in' and 'breathe out' status during diurnal and synoptic barometric pressure changes. Pressure balancing has been used for decades to manage ventilation pressure differentials across various sealed goaf areas, particularly to minimise air leakages into and out of the sealed areas. Pressure balancing chambers have also been used successfully for reducing leakages between the goaf areas in multi-seam mining conditions. In some mining conditions pressure balancing may not achieve positive results, particularly if the pillars are subjected to higher stresses or are crushed and contain many leakage paths near the edges. In such cases shifting of seals to the mid-pillar area had a significant positive effect in reducing the frequency of spontaneous combustion incidents [Fig 2 of 49].

To overcome the issues with standard pressure balancing chambers, a positive pressure chamber system was developed by the Austar team to minimise air leakage into the fire affected sealed goafs [25]. The chamber seals [Fig 6 of 25] were designed to promote the retention of positive pressure and to provide a preferred leakage path into the goaf. Nitrogen was then injected into this chamber under pressure such that a positive pressure was maintained within the chamber. There was also a provision to inject directly into the goaf at all seal locations, if required. It was reported that the positive pressure chamber system [Figs 6 & 8 of 25] has reduced spontaneous combustion risk in adjacent sealed goafs and has significantly controlled the risk of a spontaneous combustion event in an active goaf [25]. It was also reported that this system assisted in effective management of the active goaf during the longwall recovery and seal-up process.

It was reported that the positive pressure chamber system which was originally developed for sealed goaf areas has been extended to cover adjacent 'sealed goafs' as well as 'active goafs' [25]. My understanding is that the positive pressure chamber system shown in Fig 8 of [25] has been further modified with the construction of positive pressure chambers in all maingate cut-through seals around the active longwall panel goaf.

Q(6): Comments and Opinions:

- The positive pressure chamber system is an effective system for minimising air leakages through cut-through seals in 'sealed goafs'. In sealed goafs, the main source of oxygen ingress into goaf areas is leakage through the seals and/or adjoining pillar fractures and the positive pressure chamber system would be highly successful in addressing that issue.
- Although the positive chamber system would be effective in minimising oxygen ingress into the adjacent 'sealed goafs' through outbye seals, it may not be able to stop oxygen migration from the 'active goaf' tailgate area behind the face into the 'sealed goaf' through roof fracture zones under low goaf gas environments, depending on site specific conditions.
- Inert gas can also be injected directly into the adjacent 'sealed goafs' to minimise air leakages. For this inertisation strategy, the appropriate locations for inert gas injection are seals or goaf holes located at the start-up area of the sealed goaf. Sealed goaf inertisation along with an adjacent goaf gas drainage system also assists in minimising gas migration from sealed goaf into the active goaf or into the longwall tailgate return.

- If spontaneous combustion in active goaf areas is only due to air leakage through seals under some specific mining conditions, then the positive pressure chamber system may be able to minimise the risk of spontaneous combustion in such scenarios.
- As discussed in response to question 7 below, leakage through seals is only one of the contributors to total oxygen ingress into the 'active goaf areas'. So, the positive pressure balance system on its own may not be able to significantly reduce oxygen ingress into 'active goafs' and therefore would not be able to minimise spontaneous combustion (sponcom) risk, particularly in highly sponcom prone mines under thick coal seam mining conditions with substantial amounts of coal left in the goaf.

Question (7): The role of pressure chambers incorporated into goaf seals (as practiced at Austar) in regard to active goaf inertisation?

Q(7): Background Information:

Goaf gas distribution measurements at mine sites showed that air/oxygen ingress into the active goaf areas was very high as shown in Fig 1 of [7], which can lead to the development of heatings and fires in spontaneous combustion prone mines. When intake air reaches the longwall face it does so with considerable kinetic energy and this results in a relatively deep penetration into the intake side of the active goaf. A proportion of this air entering the goaf will continue to flow along the collapsed gateroad on the intake side of the goaf. Some air may eventually traverse the original face start-line also under flat seam gradient conditions. Air/oxygen can also ingress into the collapsed gateroad on the tailgate side of the goaf depending on the goaf gas drainage flow rates and strategies.

The research carried out at CSIRO that included field studies and extensive modelling studies indicated that air/oxygen ingress into the goaf depends on a number of factors including intake airflow quantities and velocities, ventilation layouts and systems, longwall panel geometry, seam gradients along and across the longwall panels, caving characteristics of the roof strata, presence of dykes and faults that can change the permeability in the goaf, support density used in the gateroads, the extent of high permeability areas adjacent to the collapsed gateroads in the goaf, curtains at the maingate intake area, goaf gas emission rates, gas composition, gas buoyancy, goaf gas drainage holes location and flow rates, goaf gas drainage operational strategies, seal conditions and leakages, and pressure differentials across the seals [7,11]. Therefore, it is to be noted that 'seal leakage' is only one of the factors for oxygen ingress into the active goafs.

Extensive modelling studies carried out without seals around the active goaf have indicated that the main source of oxygen ingress into the active goaf is from the longwall face intake airflow. Tracer gas studies carried out in active longwall panels have also confirmed this high oxygen ingress from the longwall face on the maingate side of the active goaf, with tracer gas released in the intake airflow being detected at almost 1,000m deep in the goaf [14, 17]. In addition, the literature review shows that numerous spontaneous combustion incidents have occurred around the world in longwall panels with single gateroad systems, i.e. without any cut-throughs or seals around the active goaf, indicating the only possible source of oxygen ingress is from the longwall face intake airflow.

Q(7): Comments and Opinions:

- My responses to Question 6 are also relevant to this question.
- As discussed above, oxygen ingress into 'active goafs' depends on a number of site-specific parameters and 'leakage through seals' is only one of the factors responsible for total oxygen

ingress into the active goaf areas. Therefore, the positive pressure balance system on its own would not be able to significantly reduce oxygen ingress into 'active goafs'.

- If the longwall extraction is in a thick coal seam with some coal left in the goaf or if there are roof coal seams within the caving zone of up to 15-20m height above the working seam, the positive pressure chamber system on its own would not be able to minimise the risk of spontaneous combustion in active goafs, unless an additional inertisation strategy has been implemented as a priority with inert gas injection directly into the deep goaf (particularly in highly spontaneous combustion prone mines).
- In some overseas countries, where longwall panels are developed with single gateroads without cut-throughs (i.e. no maingate seals and no seals leakage), nitrogen is injected into the active goaf through pipes deployed in the goaf from the maingate or from boreholes distributed in the caved area.
- If the decision is to use the positive pressure chamber system in combination with deep goaf inertisation for active goafs, then it is recommended to install two separate inert gas pipelines from surface inertisation plants to ensure sufficient inert gas flow rate deep into the active goaf. In that scenario, only a small proportion of the total inert gas (around 300 l/s) should be used for the positive pressure chamber system and a major proportion of the inert gas (around 1,200 l/s) should be injected directly into the deep goaf.
- In the case of the positive pressure chamber system in active goaf scenarios, the excess inert gas can either leak out to the perimeter maingate roadway or leak into the active goaf depending on the leakage characteristics of the seals and surrounding pillar fractures. Of course, the pressure chamber system can be designed to always leak excess inert gas into the active goaf. However, inert gas leakage/trickling out into the active goaf at a number of cut-throughs (runs into 30 to 40 cut-throughs during longwall finish periods) may not able to alter the goaf gas flow patterns significantly and thus may not offer any significant resistance to oxygen ingress into the active goaf from the face ventilation airflow or oxygen ingress into the goaf due to goaf gas drainage. Further research is required to investigate the effect of inert gas injection at critical locations at high flow rates versus the effect of inert gas injection through all the cut-through seals at low flow rates.
- One of the critical strategies for prevention of spontaneous combustion in active goafs is continuous monitoring of goaf gas conditions using tube bundle monitoring systems. The tube bundle points should be located some distance away (at least 50-100m) from the inert gas injection points. In the case of a standard deep goaf inertisation strategy with inert gas injection through strategic cut-through seal locations, tube bundle monitoring points can be installed in the neighbouring cut-through seals.
- However, in the case of the positive pressure chamber situation for active goafs, inert gas would leak into the goaf through all the cut-through seals and tube bundle monitoring points located in any of the seals would not give a representative sample of the active goaf atmosphere. Tube bundle points in that case should be installed in the active goaf through horizontal boreholes drilled at the centre of barrier pillars on the maingate side to get a representative sample of the goaf atmosphere at the working seam level.
- Therefore, in my opinion a deep goaf inertisation strategy with inert gas injection through a combination of strategic cut-through seals and surface goaf boreholes would provide a reliable system to minimise oxygen ingress into 'active goafs'.

Question (8): Any thoughts on the required delivery capacity of inert gas generators to implement active goaf inertisation and in particular against production rates?

Q(8): Background Information:

As discussed in response to Questions (4) and (7), research has been carried out on proactive inertisation to investigate its effectiveness in reducing oxygen ingress into the goaf under Australian mining, ventilation and operational conditions. The results of earlier research are presented in various reports and papers [7, 10, 11, 12, 39]. After the initial project [11], research continued to further advance and update proactive inertisation strategies for high production longwall mines with faster retreat rates, and the results are presented in [5].

Q(8): Comments and Opinions:

- In the early 2000's, a minimum inert gas flow rate of 500 l/s was recommended based on production rates and mining conditions.
- In the current mining environment with longer panels, high production targets of 5-10 MT per year and high goaf gas drainage requirements, studies indicate that inert gas flow rates of around 1,200 - 1,500 l/s are required for effective inertisation in active longwall goafs, particularly in spontaneous combustion-prone mines or in seams with flat gradients.
- In addition to the active goaf, the adjacent sealed goaf also presents some risk with respect to oxygen leakage and spontaneous combustion. It is recommended to inject inert gas into the adjacent goaf at the rate of around 300 - 500 l/s to minimise oxygen leakage risks as well as to assist in adjacent goaf gas drainage to minimise gas migration into the active goafs.
- As mines becomes extensive with a number of sealed panels and large ventilation networks with multiple shafts and fans, on occasion there may be a need to inject additional inert gas into other old sealed goafs, depending on the requirements.
- Taking the above into consideration, a total inert gas flow rate capacity of around 1,500 - 2,000 l/s is recommended for high production longwall mines with high spontaneous combustion risk or for mines with a previous history of spontaneous combustion incidents.
- In addition to providing adequate inert gas plant capacity at the mine site, it is also critical to continuously monitor actual inert gas flow rates at various injection points to ensure planned inert gas injection and the achievement of effective inertisation in the active goaf.
- In thin seam mining conditions or in mines with low spontaneous combustion risk with no remnant coal in the goaf or in the immediate caving zone, if required, an inert gas flow rate of around 500 l/s may be adequate for managing spontaneous combustion risk.
- As discussed in responses to Questions 11 and 13, mines may need to procure additional inert gas capacity of around 2,000 - 3,000 l/s for active goaf inertisation to assist in increasing goaf gas drainage rates and managing tailgate gas concentration levels.
- Further research is recommended to advance proactive inertisation strategies with the additional objectives of reducing oxygen migration into the goaf gas drainage holes (by replacing oxygen with nitrogen) and reducing methane gas accumulations in the goaf, in addition to the current objective of reducing oxygen ingress into the active goaf.
- If the above inertisation research is successful in increasing goaf gas drainage rates by replacing oxygen with nitrogen, the required capacity of inert gas generators would be substantially higher at around 3,500-5,000 l/s; i.e. 1,500-2,000 l/s for reducing oxygen ingress

into the goaf and an additional 2,000-3,000 l/s for reducing methane accumulations in the goaf. Inert gas may need to be injected into the goaf through a combination of strategic cut-through seals and surface goaf holes to achieve the objectives of minimising oxygen ingress into the active goafs and reducing methane accumulations in the goaf.

Question (9): Recommendations on the preferred gas for inertisation (N2 versus CO2)?

Q(9): Background Information:

Modelling studies indicate that the high permeability region in the longwall goaf in general can extend up to 15-20m high above the seam floor level, up to 20-40m wide into the goaf from the gateroads, and 50-70m deep into the goaf from the face start-up line and behind the face, depending on geological conditions. Spontaneous combustion or heating incidents can occur anywhere in the high porosity region of the active goafs. Goaf gas flow modelling studies indicated that in addition to the goaf caving characteristics and permeability distribution, gas flow patterns in the goaf also depend typically on coal seam gradients, gas emissions rates, gas composition and buoyancy in addition to other mining parameters such as longwall panel geometry, ventilation layouts, gateroad support and goaf gas drainage designs [7, 11, 17, 18, 34, 35, 51]. Studies also indicated that effectiveness of inertisation in active goafs depends on inert gas composition, flow rate, inert gas injection location and overall inertisation strategy.

Q(9): Comments and Opinions:

- Goaf gas flow studies have indicated that high oxygen levels can extend up to 15-20m high above the working seam floor level in the goaf area, in addition to high oxygen ingress at the working seam level. Field measurements in horizontal goaf holes, vertical boreholes and cross-measure holes also confirmed that oxygen can extend to up to 15-20m above the working seam depending on the caving and goaf gas emission conditions.
- It is critical that inert gas should cover most of the high permeability regions even up to 15-20m above the active goaf floor level.
- Modelling simulation with nitrogen (N_2), Boiler gas (14% CO_2, 85% N_2) and CO_2 inert gases indicated that N_2 is highly mobile and can penetrate/migrate into all the areas of the goaf where air can penetrate, i.e. where oxygen can penetrate.
- Studies also indicated that there is no significant difference between N_2 and Boiler gases with respect to effective inertisation in active goafs. However, the success of CO_2 inertisation depends on favourable seam gradients and retreating conditions.
- CO_2 has been used successfully in short bord and pillar panels retreating in the up-dip direction as a proactive inertisation strategy [35, 51]. It is to be noted here that it is very difficult to achieve effective inertisation with N_2 in bord and pillar panels due to their shorter lengths of around 120-200m.
- CO_2 would be more effective if the longwall panels are retreating in the up-dip direction, as CO_2 can fill-up the down-dip goaf areas more effectively and can remain for longer periods due to its higher density. However, it is to be noted here that with only occasional exceptions, most longwall panels in Australia retreat in the strike direction. In general, it would be difficult for CO_2 to reach high permeability regions at higher elevations without flooding the face if the seam gradients are not favourable. It is to be noted here that several spontaneous combustion

incidents have occurred even in mines with coal seam goaf gas emissions consisting of more than 50-70% CO_2 (17, 18, 34).

- Introduction of CO_2 in strike direction-retreating active longwall goafs may present an additional danger of asphyxiation due to high CO_2 or low O_2 in the case of goaf falls. In addition, there is a probability that CO_2 can leak out of the seals and may present an additional asphyxiation risk for people inspecting seals or while taking samples from the seals.
- Another critical point in assessing the practicability of a continuous inertisation strategy is the ease of operation and availability of a continuous supply of inert gas. It would be difficult to generate CO_2 at mine sites and it would need to be supplied through tankers, making it difficult to implement as a preventive strategy on a continuous basis. N_2 can be generated at mine sites and can be supplied at the required flow rates continuously, which makes it a good choice as the preferred inert gas for continuous proactive inertisation in active goafs.
- Although the use of CO_2 may not be practicable as a continuous inertisation strategy, it can still offer advantages for heating control under certain conditions such as favourable gradients, heatings in sealed goafs or active goaf heatings located far away from the face.
- It is recommended to further investigate CO_2 applications in heating control operations. Mines Rescue Stations may make appropriate preparatory arrangements for its potential applications in heating control operations, if required.
- Taking into consideration of the above points, it is recommended that N_2 be used for continuous proactive inertisation in active goafs.

Question (10): The impact that proactive inertisation may have on traditional spontaneous combustion indicators and what would be the recommended indicators to use in conjunction with active goaf inertisation?

Q(10): Background Information:

The standard indicator gases for spontaneous combustion are CO, H_2 and ethylene and different trigger levels are set at different mines based on background levels under normal mining conditions. The rate of increase in concentration levels of these gases and different ratios are used for evaluating the intensity/progress of heatings. Modelling studies have been carried out by CSIRO to simulate the behaviour of heatings and related CO and H_2 flow patterns in longwall goafs [7, 40]. The predicted gas distribution patterns of CO produced during early stages of heating development are shown in Fig 4 of [7]. The results indicate that CO produced from a heating on the MG side would disperse over a wide area in the goaf before reporting to the longwall return airflow.

The field measurements of goaf gas readings presented in Fig 7 of [7] also confirm that CO readings in the goaf would reach 100's of PPM before a significant change in CO levels is recorded in the longwall tailgate return roadway. The results indicate that continuous goaf gas monitoring at strategic locations is critical for detection of heatings at the early stages, as substantially higher readings can be measured in the goaf long before any significant increase in CO readings in the tailgate return roadway is noticed. A schematic of the recommended goaf gas monitoring system showing the appropriate locations of tube bundle monitoring points for the active goaf is presented in Fig 10 of [7]. Field experience in several cases with proactive inertisation has shown that CO can still be detected in the active goaf during early stages of the heatings, if comprehensive goaf gas monitoring systems have been implemented at mine sites.

Laboratory evaluation of the spontaneous combustion propensity index parameters and the traditional spontaneous combustion indicators are presented in various reports and papers [19, 24, 27, 36, 48]. Problems with determining oxygen deficiencies for use in ratios used for assessing spontaneous combustion activity are highlighted in [24]. It was highlighted in that paper that interpretation of data is best done by looking at trends rather than one off samples. Even if the ratio is being underestimated, any increase in intensity should result in an increase in the trend although the rate of change may not match the increase in intensity.

Q(10): Comments and Opinions:

- Studies indicate that goaf gas emissions, drainage rates, caving characteristics, ventilation layouts, inert gas flow rates and injection locations, and overall proactive inertisation strategies will all have a significant effect on heating gases flow behaviour, diffusion, dispersion patterns and concentration levels at different locations in the active goafs. Therefore, it is very important to take the above parameters into consideration while interpreting goaf gas readings and when trying to estimate the heating intensity/ location.
- Although proactive inertisation impacts on traditional spontaneous combustion indicators close to its injection points, studies indicate that CO readings can still be detected at seal samples close to the heatings or in seal samples located at 50-100m away from the inert gas injection points in case of heating development in the active goaf areas.
- In general, high CO gas concentrations can be detected at the working seam level, i.e. in gas sampling at cut-through seals much earlier than high H_2 readings due to the density difference between these two gases and buoyancy effects in the goaf areas. At significantly elevated heating conditions, both CO and H_2 can be detected at higher concentration levels in the seals gas samples.
- CO, H_2 and ethylene concentration values remain good spontaneous combustion indicators even under continuous proactive inertisation conditions, taking into consideration background concentration values under normal mining conditions. However, interpretation of goaf gas readings should take into consideration the inert gas injection locations and flow rates, goaf gas flow patterns and other conditions in active goafs.
- In active goafs with continuous proactive inertisation scenarios, trends of heating gas concentration values and trends of various ratios are highly critical in assessing the progress of spontaneous combustion/heating conditions.
- Research studies and field measurements indicate that in the case of deep seated heatings, CO readings in the goaf would reach 100's of PPM before a significant increase in CO levels is recorded in the longwall tailgate return roadway. Therefore, continuous goaf gas monitoring at strategic locations in an active goaf at working seam level is critical for detection of heatings at the early stages. It is to be noted that simply depending on heating gas concentration levels in the longwall return roadway or at other outbye locations is not a good strategy for achieving high standards of safety in active longwall goafs.
- One of the critical strategies for prevention of spontaneous combustion in active goafs is continuous monitoring of goaf gas conditions using a tube bundle monitoring system. The tube bundle points should be located at some distance away (at least 50-100m) from the inert gas injection points. In the case of a standard deep goaf inertisation strategy with inert gas injection through strategic cut-through seal locations, tube bundle monitoring points should be installed in the adjacent cut-through seals, i.e. in the seals without inertisation.

- If a high CO reading is detected in any of the seal samples, inert gas should be injected on the inbye side (not on the outbye side) of the high CO reading location to control the heating. It is to be noted that inert gas injection through the same cut-through where a high CO reading has been detected may result in misinterpretation of the heating status and there is a possibility that the inbye heating will continue to develop to a more advanced stage.
- At least 6 to 8 tube bundle points should be installed for goaf gas monitoring in active goafs for each longwall panel under spontaneous combustion proneness conditions. It is to be noted that these 6 to 8 goaf gas monitoring points should be in addition to the other tube bundle points installed in the longwall panel to monitor intake, return, perimeter and other outbye locations in and around the panel.
- It is also important to continuously relocate some of the goaf gas monitoring points and inert gas injection locations along with the longwall retreat. As a general rule, inert gas injection and goaf gas monitoring should be in different cut-through locations.
- In addition to tube bundle monitoring, it is important to collect goaf gas bag samples at regular/ fortnightly interval from all the seals in active goafs and from selected seals of the adjacent sealed goaf.
- The traditional indicators such as CO, H_2 and ethylene concentration levels will continue to be good/recommended spontaneous combustion indicators even in conjunction with continuous proactive inertisation in active goafs, subject to implementation of continuous goaf gas monitoring system with sufficient number of tube bundle points installed at appropriate cut-through seal locations.

Question (11): Any thoughts on how to manage goaf drainage in combination with active goaf inertisation?

Q(11): Background Information:

Development of high capacity goaf gas drainage systems in a spontaneous combustion prone mine requires a fundamental understanding of goaf gas flow mechanics in the longwall goaf. As discussed in response to Question (4), goaf gas flow mechanics is a very complex process and depends on a number of geological, mining and operational parameters at specific mine sites. CSIRO research studies have included goaf gas distribution monitoring, tracer gas investigations, caving modelling and computational fluid dynamics modelling simulations. The details and results of the goaf gas drainage and inertisation research under different goaf gas conditions are presented in various reports and papers [4, 5, 7, 11, 17, 18, 34, 43, 44, 52]. The research has developed a fundamental understanding of gas flow mechanics in longwall goafs and has provided a detailed understanding of the effect of various goaf gas drainage and inertisation strategies on oxygen ingress patterns in the longwall goafs. The insight into goaf gas flow mechanics from those studies was then used by CSIRO for the development of innovative and efficient goaf gas drainage and inertisation strategies for highly gassy spontaneous combustion prone mines.

In active goafs, oxygen ingress into the goaf will be very high on the maingate side due to the longwall maingate intake airflow kinetic energy and lower elevation of the maingate in general. It is to be noted that goaf gas drainage holes are normally located on the tailgate side of the goaf to take advantage of the lower ventilation pressures on the tailgate return side and gas buoyancy pressures, as the tailgate roadway is generally located at higher elevations. The oxygen ingress on the tailgate side of active goafs depends on total goaf gas emissions, gas composition, gas drainage rates and goaf hole design and drainage/ operational strategy. Current goaf inertisation strategies generally involve injection of inert gas into the deep goaf through cut-through seals located on the maingate side of active goafs.

Q(11): Comments and Opinions:

- Goaf gas drainage without any proactive inertisation in active goafs generally leads to increased oxygen ingress into the active goafs, depending on gas emissions, gas drainage rates and other mining and operational conditions.
- N_2 generally replaces air in active goafs as both N_2 and air have similar densities and flow characteristics, subject to proper design and implementation of goaf drainage and inertisation systems.
- Preliminary studies were carried out to investigate the effect of current proactive inertisation strategies on goaf gas drainage and longwall return gas levels. These studies indicated that inert gas injection into deeper locations in the goaf can assist in increasing goaf gas drainages rates through surface goaf gas holes by replacing some O_2 in the goaf holes with N_2.
- In general, up to 20-30% of the injected inert gas may end up in surface goaf holes, based on the design of goaf gas drainage and inertisation systems. Therefore, goaf gas drainage capacity should be high enough to account for additional drainage of a significant proportion of inert gases introduced into active goafs.
- It is to be noted that if the goaf gas drainage capacity is not sufficient to take care of a significant proportion of the inert gas injected, there is a possibility of slightly reduced methane gas drainage for the same total drainage rate under some circumstances, and an increase in tailgate return gas concentration levels.
- Proactive inertisation in the longwall goaf involving injection of inert gas directly into the goaf at strategic deep locations, i.e. at the inbye locations, at high flow rates would be the suggested effective and practical strategy under normal longwall retreat operations. Studies indicated that inert gas should be injected into the deep goaf (at least more than 200m behind the face) at multiple strategic points to minimise oxygen ingress into the active goaf.
- Injection of inert gas deep into active goaf permeable regions would allow the inert gas to fill the goaf and spill out towards the face which assists in minimising oxygen ingress into the goaf. In addition, injection of inert gas deep into the goaf will be more effective and require lower volumetric rates than shallow inert gas injection.
- As longwall panels in general will not have any surface boreholes on the maingate side (although recently at a few mines, surface boreholes have become available on the maingate side), research so far has concentrated on developing appropriate strategies for inert gas injection through maingate cut-through seals to facilitate practical implementation of the proactive inertisation strategy as a continuous practice along with longwall retreat operations.
- Properly designed and implemented proactive inertisation strategies would also assist in increasing goaf gas drainage rates in addition to minimising oxygen ingress into active goafs.
- Continuous proactive inertisation into the inbye sections of the active goafs in combination with goaf drainage offers the following benefits/advantages:
    - Reduces oxygen ingress into active goafs – reduces air ingress from the longwall face as well as minimising air leakage through the seals
    - Assists in increasing methane gas drainage rates (by replacing oxygen in goaf holes with nitrogen) and displacing deep goaf methane towards goaf holes

  - Assists in dispersion of heat generated due to oxidation in the goaf (and reduces heat accumulation in the goafs)
  - Reduces methane gas accumulations in the goaf, which assists in reducing the effects of barometric pressure variations and goaf falls.

- So far, inertisation research and studies have been focussed only on reducing oxygen ingress into active goafs. Further research is recommended to advance continuous inertisation technologies for active goafs to achieve the twin objectives of increasing goaf gas drainage rates and minimising oxygen ingress. This research may include studies with inert gas injection through surface boreholes as well as through the maingate cut-through seals to assist in minimising oxygen ingress into the gas drainage holes and into active goafs.

Question (12): Recommended practices in terms of ventilation pressures over goaf seals and around goafs?

Q(12): Background Information:

Field measurements at mine sites indicate that ventilation pressure differentials across the seals in ‘sealed goafs’ can vary between 500Pa and 4,000Pa depending on the type of seals, construction location and procedures, depth of mining, pillar design, goaf gas emission rates and other conditions. In contrast to sealed goafs, the ventilation pressure differentials across the seals in ‘active goafs’ would be only in the order of 50-150Pa, either breathing-in or breathing-out, in Australian mining conditions and sealing practices. Air leakage characteristics of different types of seals/stoppings under different ventilation pressure differentials across the seals are presented by Singh et al [42]. The results indicate that the air leakages through seals/isolation stoppings may be considered as satisfactory up to a ventilation pressure differential of 140Pa.

Q(12): Comments and Opinions:

- To minimise air leakage into sealed goafs or to minimise gas migration from sealed goafs to an active goaf or to the ventilation system, ventilation pressure differential across the ‘sealed goafs’ seals may be maintained at around 1,000-2,000Pa. This may be achieved through adjacent sealed goaf gas drainage under high gas emissions scenarios. In low to moderate gas emission conditions, sealed goaf inertisation or pressure balancing around the sealed goaf seals is recommended to minimise air leakage into the sealed goafs.
- Ventilation pressure differentials across various seals around an active goaf vary widely and there may not be any uniform pressure gradient along the collapsed gateroads in an active goaf, as it can vary widely depending on caving conditions, junction collapses, goaf gas emissions, barometric pressure variations and goaf falls at different locations in the goaf.
- In general, ventilation pressure differentials across active longwall goaf seals can vary from negative 150Pa (breathing-in) to positive 150Pa (breathing-out), depending on various mining and operating conditions, including the time of measurements.
- It should be noted that ventilation pressure differentials across the seals should be measured in the field, not estimated based on modelling studies as they can vary considerably depending on the actual goaf caving conditions, goaf falls at different locations, and barometric pressure variations.

- Air leakage across the seals in active goafs depends on the actual ventilation pressure differential across different seals, but not on the total ventilation pressure differential between the perimeter roadway at the start-up area and the longwall tailgate corner.
- In summary, it is difficult to specify ventilation pressure differential limits for goaf seals due to wide variations in field conditions and barometric pressure changes. The ventilation pressure differentials across the seals in 'active goafs' should be as low as possible, and it is preferable to maintain some positive pressure in 'sealed goafs' to minimise oxygen ingress. As a general guidance, the suggested ventilation pressure differentials across the seals under various scenarios are as follows: (i) Across the seals in sealed goafs – around 1,000-2,000Pa positive pressure; (ii) Across the seals in active goafs – less than 200Pa; (iii) Pressure differential between the perimeter roadway at the start-up area of the panel and the longwall face tailgate return corner – less than 1,000Pa in the case of perimeter intake, and to be less than 2,000Pa in the case of perimeter return.

Question (13): Any comments you believe should be made in the management of active goafs in gassy mines?

Q(13): Background Information:

The rate of goaf gas emissions in Australian longwall mines has increased significantly over the last two decades, and will further increase steeply from the current gas levels due to the higher insitu gas contents of coal seams at greater depths and high longwall production rates targeted from new generation longwall mines. Several research projects have been conducted over the years in Australia and overseas on post-drainage in longwall goafs using surface goaf hole drainage technologies. Initial research in the USA led to the relocation of surface goaf holes from the centre line of panels to the tailgate side for improved goaf hole performance, i.e. goaf holes producing for longer periods [28]. However, the steep rise in goaf gas emission rates necessitated development of step-change advancements in goaf gas drainage technologies, including the development of additional goaf gas management strategies.

Development of high capacity goaf gas drainage systems in a spontaneous combustion prone mine requires a fundamental understanding of goaf gas flow mechanics in the longwall goaf. As discussed in previous responses, goaf gas flow mechanics is a very complex process and depends on a number of geological, mining and operational parameters at specific mine sites. The details and results of the research and the recommended goaf management strategies and risk mitigation strategies for active goafs are presented in various reports and papers [4, 5, 6, 8, 9, 13, 14, 17, 18, 21, 22, 28, 34, 41, 44]. The research has developed a fundamental understanding of the effect of various parameters on gas flow distribution patterns in longwall goafs and assisted in the development of comprehensive goaf gas management and risk mitigation strategies for active goafs.

Q(13): Comments and Opinions:

- It is recommended that the strategy of 'Goaf gas drainage maximisation' should be adopted to minimise methane accumulations in active goafs.
- A goaf gas drainage maximisation strategy involves draining all the goaf gas that can be drained from active goafs and adjacent sealed goafs at safe gas concentration levels, even if it appears that this strategy is simply increasing goaf gas drainage rates unnecessarily.

- Goaf management strategies should include goaf gas drainage maximisation strategy in combination with appropriate continuous inertisation strategies to reduce the risks of goaf gas rush onto the longwall face and spontaneous combustion in active goafs.
- A goaf gas drainage maximisation strategy may involve a combination of gas capture strategies, such as tailgate drainage goaf holes, maingate drainage goaf holes, panel centreline drainage goaf holes, tailgate cut-through goaf hole drainage, deep goaf gas drainage, adjacent sealed goaf gas drainage, goaf gas drainage from a number of goaf holes, and additional vertical and horizontal goaf holes in the start-up area, etc.
- It is to be noted that remnant goaf gas not drained or not migrated to the longwall return will start accumulating in void spaces of the longwall goaf at higher elevations. Accumulation of methane in an active goaf significantly increases the risk of gas rush onto the longwall face and tailgate return during barometric pressure variations or goaf falls in active goaf areas. Any major goaf falls during diurnal low barometric pressure periods can result in significant goaf gas displacement onto the longwall face.
- It is recommended to minimise high concentration methane accumulations in active goafs to minimise the risk of gas rush onto the longwall face or tailgate return during low barometric pressure periods or goaf falls.
- Continuous proactive inertisation strategy with inert gas injection directly into the inbye sections of the active goaf should be designed and implemented to increase methane drainage rates in the goaf areas, through displacement of some oxygen in the goaf gas drainage holes. This strategy also involves installation of additional goaf drainage capacity to account for some proportion of the inert gas injection flow rates into the goaf areas.
- Inertisation goaf holes should be drilled down to within 5-10m of the working seam to inject inert gas directly into the active goaf at the designed strategic locations.
- Surface goaf holes and drainage strategies should be designed and operated to make a significant change in gas flow patterns in order to reduce goaf gas migration towards the longwall face and tailgate return. Deep goaf gas drainage in combination with increased inertisation into the inbye sections of the active goafs assist in achieving this objective.
- It is known that a ‘tailgate back-return ventilation system’ assists in reducing goaf gas migration towards the tailgate drive motor area. However, to implement the tailgate back-return system longwall panels need to be developed with a 3 gateroad system, which itself presents other problems such as a significant increase in the explosive fringe area into the second roadway behind the face. Therefore, tailgate goaf holes can be re-designed and operated in such a way to assist in achieving the benefits of a tailgate back-return system.
- To achieve the benefits of a ‘tailgate back-return system’, some of the surface goaf holes may need to be drilled down to within 5-10m of the working seam. The perforated casing length in the goaf holes should cover all the overlying coal seams.
- All surface goaf holes should be able to be operated at different flow rate capacities. Surface goaf gas drainage holes at different locations should be operated at different capacities, depending on methane and oxygen levels.
- The last 5 to 8 shields (powered roof supports) at the tailgate end of the longwall face may need to be re-designed to offer more open space at the back of the shields to assist in diverting some of the face airflow towards goaf to continuously scour goaf gas and prevent methane accumulations in the tailgate corner area of the goaf. This strategy would assist in minimising goaf gas rush events that normally happen when the shearer is approaching the

tailgate. In addition, the tailgate drive motor may need to be repositioned by a few meters towards the maingate side to keep it further away from the tailgate corner. Further research is recommended into these chock redesign and tailgate drive motor re-positioning topics to carry out detailed feasibility investigations, and to optimise designs and locations.

- It is to be noted that it would be very difficult to achieve effective inertisation within 100m behind the face, i.e. the permeable area immediately behind the face. However, the immediate permeable area behind the face would be exposed to oxygen only for one to two weeks as the longwall retreat rates would be more than 70-100m/week in standard operating conditions. Therefore, from the spontaneous combustion point of view, it is not a major risk in fast retreating longwall panels.
- In some circumstances such as when a longwall face stops, for example due to breakdowns within 100m outbye of the fault areas in the goaf or when it is expected to take considerable time (i.e. more than a few weeks) for face withdrawal at the finish line, it is recommended to use additional control measures to minimise spontaneous combustion risk. It is recommended that inert gas flow rates into the active goaf should be increased significantly with additional inert gas injection through 3 to 4 new surface boreholes drilled at 30-70m behind the face. Additional inert gas injection behind the face through boreholes assists in dissipation of heat generated due to coal oxidation and assists in reducing the rate of oxidation/ spontaneous combustion in the permeable area immediately behind the face. Additional control measures such as foam injection or foaming concrete or fly ash plugs in the collapsed gateroads behind the face may also be used, if required.
- Further research is recommended to advance goaf management strategies to maximise goaf gas drainage rates and reduce methane accumulations in active goafs. Future research should include (i) increased continuous inert gas flow rate injection into active goafs to minimise oxygen ingress into goaf holes and increase goaf gas drainage flow rates; (ii) intelligent real time monitoring and dynamic control of individual goaf holes; (iii) re-design of tailgate area chocks to minimise methane gas accumulations just behind the face; and (iii) development and evaluation of additional strategies to minimise spontaneous combustion risk in the start-up areas of the panels, near fault areas, and during longwall take-off periods.

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