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A QUANTITATIVE APPROACH TO ENGINEERING FIRE LIFE SAFETY IN MODERN UNDERGROUND COAL MINES

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ABSTRACT: Emerging from a history of 'blanket approach' prescriptive fire protection design, underground coal mining is rapidly embracing fire life safety analysis techniques that have been successfully used in performance-based fire engineering in the built environment.

In Australia, the leading practice fire engineering approach is to apply the International Fire Engineering Guidelines (ABCB 2005) and its methods as a design assessment framework. This approach has recently been used to quantify the performance of mine fire detection and therefore control of fire spread, paving the way for improvements in mine fire intervention and mine worker escape.

This paper presents a method of early fire detection using closed circuit television cameras and video analysis software associated with fixed plant fires leading to increased available safe evacuation time compared with contemporary point type fire detectors and gas monitoring sensors.

Successful pilot tests of the fire detection technology have been carried out in simulated mine conditions. A quantified and scientifically informed risk-based approach, offering improvements in mine fire rescue intervention and evacuation methodologies was achieved.

INTRODUCTION

The problem of mine fires is not a new problem for mine safety practitioners, with most research to date addressing the natural phenomenon of spontaneous combustion of coal. Similarly, a significant amount of research has previously been carried out involving potentially flammable gases released during mining operations. The subject research examines the lesser-understood problem of fires associated with fixed plant.

The current approach to fire detection in underground coalmines involves a reliance on gas analysis systems, rather than fire detection systems. The gas analysis systems are used to detect the concentration of carbon monoxide in air, which is not considered in the subject research to be appropriate for the detection of smoke in relation to fixed plant fires.

Carbon monoxide sensors, especially those distributed at various points within the mine workings, have a tendency to drift and become inaccurate over time. The more traditional tube bundle gas analysis approach, involving the remote collection of samples through tubes, inherently involves significant transport delays between the time of collecting the sample air and the time required to analyse the sample.

A recent comparative study by the National Institute for Occupational Health and Safety (NIOSH) (Edwards, 2002) was carried out in the NIOSH test mine. The tests evaluated the effectiveness of fire detectors and gas analysis sensors and showed that CO sensors were not as effective as smoke detectors for early fire detection of smouldering belt particulates.

Experimental results showed the clear advantage of smoke sensors over CO sensors for early mine fire detection. It was shown that smoke sensors could detect smouldering belt combustion smoke particulates long before alarm levels of 5 ppm CO were detected (Edwards, 2002).

Early fire detection is considered a critical aspect of mine fire life safety and asset loss control due to the potentially onerous evacuation and intervention considerations associated with the operational mining

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environment. The subject research assesses an emerging technology of early fire detection referred to as Video Based Fire Detection (VBFD). This technology is used to detect the early onset of fixed plant fires and is considered to be an efficient solution for early fire detection in underground coalmines.

Fixed plant equipment, where VBFD might be used in mining, includes: conveyor systems; refuelling stations; and electrical installations, however it is not limited to these examples. This improved fire detection technology applies Closed Circuit Television (CCTV) and video analysis algorithms to the video images to automatically recognise early fire development and subsequently initiate fire intervention.

For the purpose of quantifying the effectiveness of this technology, the International Fire Engineering Guidelines IFEG (ABCB 2005) is considered a suitably robust assessment framework.

VOLUME DETECTION - A NEW APPROACH FOR DETECTING MINE FIRES

Point type fire detection

Based on recent observations in underground coal mines and discussions with miners, it is reported that coal miners rely on point type gas analysis systems, such as remotely located carbon monoxide sensors, as their primary means of fixed plant fire detection.

Gas sensors are intended for the measurement of diffused carbon monoxide. The source of the carbon monoxide is typically that produced from the spontaneous combustion of coal or belt material. These types of gas analysis systems are not designed, intended, suitable or certified for the detection of combustion products associated with fixed plant fires.

The Australian Standards approved point type smoke detector (Figure 1) is certified under a system that is similar to many international approval systems. It is designed, tested and approved for the purpose of early fire detection, but intended for use in commercial facilities and not mines. It is the only current but impractical alternative to point type gas analysis systems as used in underground coalmines.

Figure 1 - Typical point type smoke detector

The point type fire detection system is configured using various types of certified fire protection point detectors, such as smoke, heat or gas detectors, or a combination of these. Point type fire detection may also describe Multi-point Aspirated Smoke Detection (MASD), where gas or smoke is remotely drawn through a single point or multiple entry points in a network of pipes, then centrally sampled. This approach is similar to tube bundle gas analysis systems used in the majority of Australian coalmines, however even with multiple detection sampling points in each sampling pipe, it is still considered a point type detection system.

The very design nature of point type detection incorporates its inherent limitation, which results from gaps in detection capability between detection points. Realistically, a detection point may not be located in the vicinity of a fire, so a delay in detection must occur.

Smoke, heat or gas is required to migrate from the fire source to the nearest point type fire detector before a fire alarm can be generated. A transport delay of smoke, gas or heat to detectors reduces the Available Safe Evacuation Time (ASET) before the onset of potentially untenable conditions. Under growing fire conditions, increasing levels of fire suppression capacity is subsequently required to control the advancing fire spread.

Inefficient fire detection not only reduces ASET for mine worker escape, but mine fire rescue and intervention capacity is reduced due to increasing fire spread.

A further major roadblock to early fire detection in mining is the physical contamination of point type detection devices from mining pollutants, whether it is individual detectors or aspirated systems with remote sensing heads. For example, point type smoke detectors using either the ionisation detection technique or the photoelectric detection technique, are readily contaminated by coal dust, which leads to false alarms and subsequent alarm complacency by occupants and mine controllers.

Volume type fire detection

Volume type fire detection involves the use of a form of detection, where the total space, or at least a substantial part of it, is monitored for early fire growth.

The most important aspect of this approach is that it excludes the need for smoke, heat or gas to physically come in contact with the sensor elements, unlike typical point detectors. Volume type detection is considered to be a potential solution to the problem of gas sensor drift and fire detection delays.

VBFD - AN EMERGING VOLUME TYPE FIRE DETECTION TECHNOLOGY

VBFD is an emerging volume type smoke and flame detection technology that utilizes CCTV cameras to capture real time video data for analysis. This detection technology offers considerably faster response times than other forms of fire detection currently used in underground mines.

VBFD cameras are enclosed within explosion protected (EX Rated) housings with no direct contact between the camera lenses and the mine environment. This makes VBFD more resistant to contamination from mine pollutants than point type smoke detectors. VBFD is seen as a solution to the problem of air pollutant contamination and subsequent unreliable early fire detection in underground mining and similar environments. Figure 2 shows a VBFD image taken in an experimental mine environment. Note the outline of the detected smoke in the image, as generated by the analytics of the VBFD system.

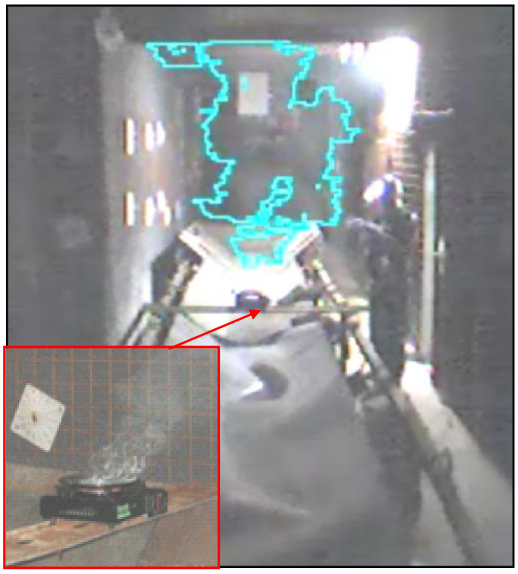

Figure 2 - Video detection of coal fire - experimental pilot tests, Wollongong 2010

Therefore, the proof of concept trial undertaken in Wollongong has shown 'volume type' detection has been achieved using VBFD.

CCTV that is configured as VBFD is the proposed means of achieving volume type fire detection in mining (Refer to Figure 3).

Figure 3 - CCTV camera suitable as a video based fire detector

On-site observations indicate that mines currently having major fixed plant items monitored by CCTV systems, such as conveyor belt transfer points, would readily and cost effectively be able to incorporate volume type fire detection into their mine fire protection systems.

The existing cameras could be utilised in illuminated areas at a relatively low cost to operate as both VBFD and for the original intent, being surveillance and monitoring of belt blockages.

IFEG - A FRAMEWORK FOR ANALYSING MINE FIRE SAFETY

The visual early warning sign of fire, in relation to conveyor systems in coal mines, is the production of smoke as a result of overheating of conveyor components, such as pulleys and bearings. This event is generally followed by increased production of carbon monoxide as a result of the oxidation of coal in the vicinity of the overheated parts, and subsequently the burning of the fixed plant components themselves.

In addition to belt systems in underground mines, other potential fixed plant fire risks involve refuelling bays and equipment where electrical arcing and overheating may occur. Early detection of combustion products is a significant factor therefore in minimising loss through early fire intervention by achieving early fire suppression and evacuation where applicable.

The current internationally accepted framework for fire engineering, which provides a guideline to the assessment approach but does not specifically stipulate the methodology, is the International Fire Engineering Guidelines (ABCB 2005). This document is referred to within the fire engineering profession as the 'IFEG'.

The New South Wales Guideline for the prevention, early detection and suppression of fires in coal mines MDG1032 (NSW-DP1 2010) is a useful document to be used in conjunction with the IFEG. MDG1032 provides context to the assessment, because it suggests mine specific guidance for the establishment of a risk-based approach to early detection and suppression of fires in coalmines.

It is understood that the IFEG methods were not initially intended for mining applications and that the analysis of mine fire safety has not previously been carried out using the IFEG format. The unique and challenging opportunity was to apply the established systematic fire risk analysis approach of the IFEG in the context of underground mining.

The scope of the IFEG framework is as follows: "These Guidelines have been developed for use in the fire engineering design and approval of buildings. However, the concepts and principles may also be of assistance in the fire engineering design and approval of other structures such as ships and tunnels, which comprise of enclosed spaces." (ABCB 2005).

The IFEG framework

The IFEG framework is divided into 'Sub Systems' within the fire engineering process. A pictorial description of the IFEG Sub Systems (ABCB 2005) is provided in Figure 4.

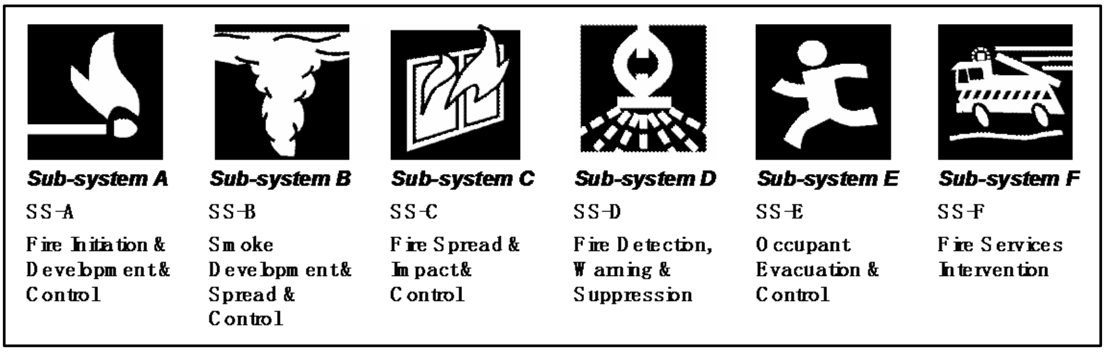

Figure 4 - IFEG fire engineering assessment framework (ABCB 2005)

Related mine fire engineering analysis

Further motivation for applying the IFEG in a coal mining context was derived from previous studies of mine evacuation under fire emergency conditions (Gao, *et al.*, 2008).

Scoping studies have also been achieved into the application of performance-based fire engineering design in relation to spontaneous combustion fires (Deng, *et al.*, 2008). These previous works are examples of a growing interest in the application of a defined fire-engineering framework to mining.

This area of interest has been assessed previously by Gillies and Wu (2004), but this work did not apply the systematic IFEG approach. This work was part of an Australian Coal Association Research Program (ACARP) research grant (Refer Figure 5).

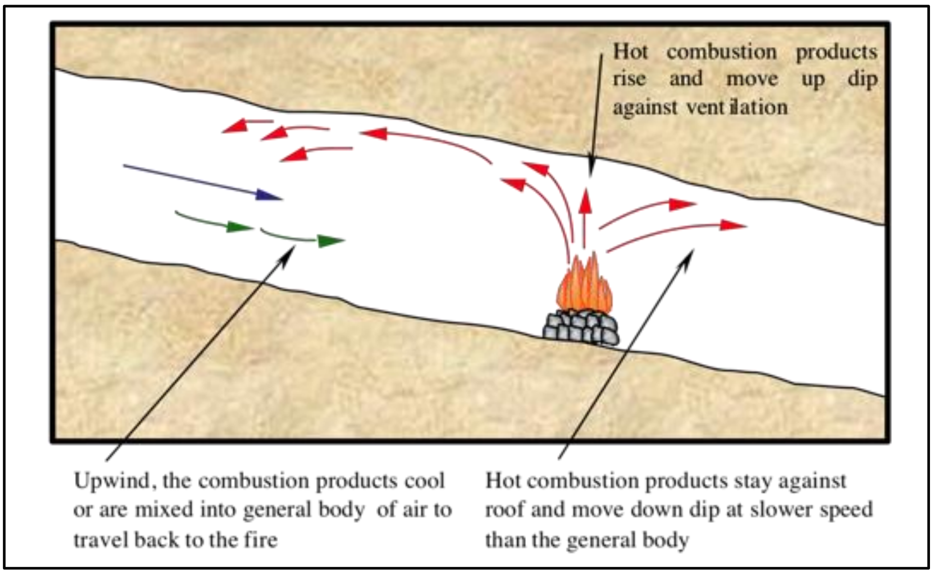

Figure 5 - Mine fire smoke movement (Gillies, 2004)

Gillies and Wu's work involved the computer analysis of a range of mine fires to understand factors, such as rescue responses, preplanning of escape scenarios, and general interaction with mines rescue organisations. The research utilised the Polish fire simulation software 'Ventgraph', in relation to smoke movement under ventilation conditions.

APPLICATION OF THE IFEG

IFEG sub-system A - Fire initiation and development and control

The development of a design fire is a critical first step in analysing the fire development within the mine. A design fire describes graphically, the characterisation of a fire in terms of its growth and its decay, shown as Heat Release Rate (HRR) in Kilowatts over time.

Analysis of the design fire and knowledge of its characteristics is required for all of the Sub-System stages of the IFEG assessment that follow Sub-system A, as described in Figure 4.

The purpose of very early fire detection is to detect the fire in its earliest growth stages, which may or may not exhibit a flaming fire. This is typically the case in fixed plant fires involving overheated bearing houses, hot idler pulleys and similar components.

Figure 6 describes a design fire typical of smouldering fuel that never reaches a flaming stage. The heat release rate reduces over time as the fuel converts to char or the applied heat supporting the low level combustion is removed. This design fire curve represents the experimental heating of powdered coal in the pilot tests in this research. The pilot test was intended to simulate smouldering coal on the surface of an overheated bearing housing.

Compare this design fire curve with Figure 7, which shows a design fire that increases rapidly in heat release rate following flaming combustion, flashes over and then decays. This type of fire is of great interest to early fire detection, as it typically produces very little carbon monoxide and therefore may not be detected by carbon monoxide gas sensors.

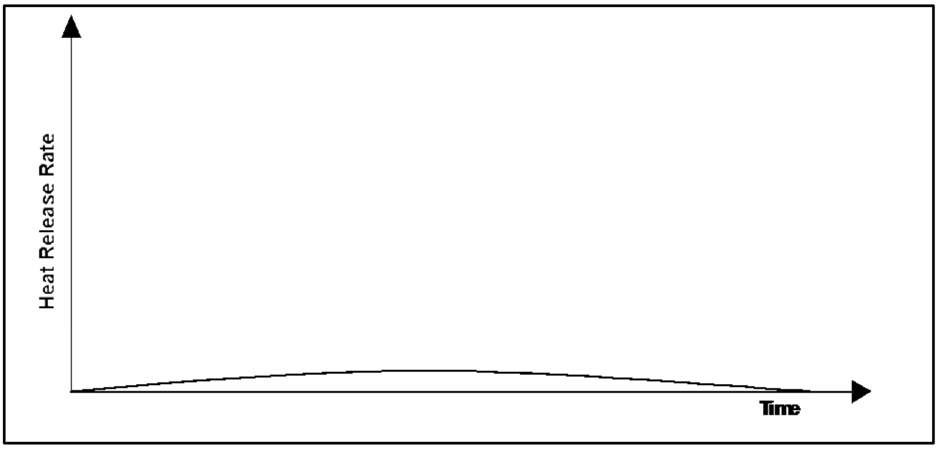

Figure 6 - Design fire curve for smouldering coal fire (Edwards, 2002)

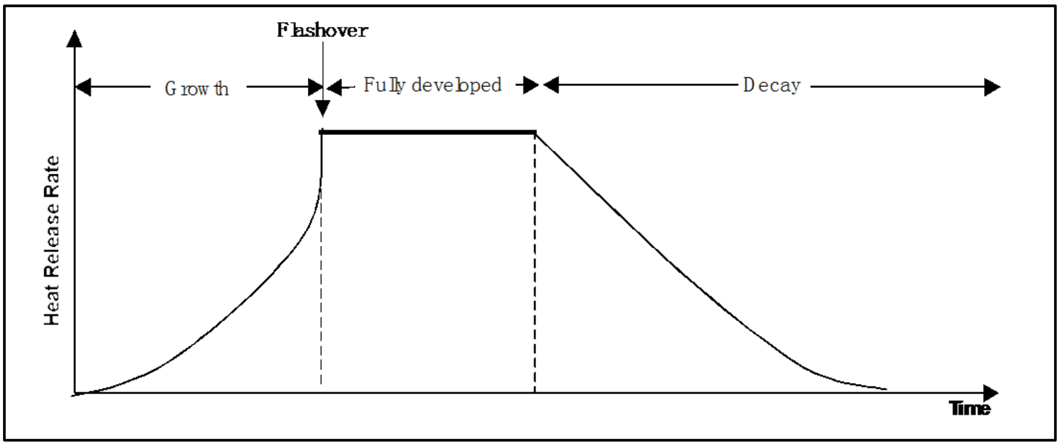

Figure 7 - Full extent design fire curve (ABCB, 2005)

Pilot tests carried out during 2010, as shown in Figure 2, simulated a portion of an overheating bearing housing surface covered in 15 mm of coal dust.

For each of the multiple tests carried out, the heated coal dust generated visible smoke within four minutes when heated to approximately 400 ^{o}C.

A low energy design fire, having smouldering characteristics for a considerable time period, resulted in each pilot test and graphically represented, would be typical of that shown in Figure 6.

IFEG sub-system B - Smoke development spread and control

An iterative process that quantifies the energy of the developing design fire for each increment of its growth is applied beyond early smouldering. This analysis is carried out through stages of growth to eventual flashover and subsequent smoke spread outside the enclosure of origin. Stages of fire growth beyond smouldering were not addressed in this study, as the focus of the study involves the analysis of early fire detection.

The management of smoke in a mine is assisted using Computational Fluid Dynamics (CFD) to estimate smoke spread scenarios under operation or non-operation of smoke barriers and whether controlled leakage through barriers is manageable. CFD is particularly useful for analysing smoke development and spread under various ventilation scenarios and has been applied in this research.

IFEG sub-system C - Fire spread and impact and control

Quantitative analysis methods, including Event Tree Analysis (ETA) validated using Monte Carlo probability simulation techniques, are applied to estimate and represent the probabilistic outcomes relating to fire spread. A range of data from previous fire science research and mine fire statistics, characterises the methods applied.

Determining the fire load density of the combustibles within the location in which the fixed plant fire has developed and spread is critical for estimating the likely severity of the fire, therefore a location specific knowledge of the environment is critical.

Understanding the impact of fire on structural elements at the affected location within the mine is a significant factor in managing mine roof collapse and therefore maintaining emergency egress. The onset of untenable conditions, in terms of heat, smoke, toxic vapor and potential explosion is equally a key factor for achieving mine worker escape or access to refuge.

IFEG sub-system D - Fire detection, warning and suppression

IFEG Sub-system D deals with fire detection and suppression. Whilst fire suppression analysis is not dealt with in this research, the IFEG provides a robust basis for the analysis of water-based fire suppression systems.

Interestingly, the IFEG does not offer a specific methodology for the volume type fire detection approach outlined earlier in this paper, primarily due to the recent evolution of VBFD and the lack of available test protocols.

The subject research addresses the application of VBFD in mining by comparing it with existing fire detection methods, as well as with currently applied gas analysis techniques. The measures of success have been based on:

- Does video based fire detection VBFD provide reliable early detection in the mining environment? (Addressed under sub-section D of the IFEG)
- Is it possible to significantly increase ASET using VBFD? (Addressed under sub-section D of the IFEG)
- Is it possible to use VBFD to assist in Mines Rescue intervention? (Addressed under sub-section E of the IFEG)?

Testing the reliability of VBFD to operate in the mining environment is ongoing. Results from pilot tests of VBFD under simulated mine conditions have achieved a repeatable response to detect low levels of smoke from incipient burning of coal at an early stage. Reliable early detection using VBFD appears to be present under simulated conditions.

The benefit of VBFD over current forms of fire detection is that it uses a volume detection approach, which is considered more effective than a point detection approach used by smoke detectors and similar fire detectors. Additionally, VBFD sensitivity is not subject to drift or chemical cross interference, as are current gas analysis sensing techniques.

"At a battery-charging station, several hundred ppm of H_2 produced a false indicated CO alarm value because of chemical cross interference in the CO sensor's chemical cell. Without the smoke sensor signal, the battery-charging activity would be considered a fire." (Edwards, 2002)

IFEG sub-system E - Occupant evacuation and control

Occupant evacuation analysis estimates the time taken for the events that makes up the mine evacuation. It does this to determine the time required for mine occupants to reach a place of safety, whether it is a mine refuge or a location outside the mine. This is referred to as Required Safe Evacuation Time (RSET).

Improved early fire detection capability assists in increasing the available safe evacuation time ASET with the aim of ensuring ASET > RSET.

Methods referenced by the IFEG analyse cue periods, response periods, delay periods and movement periods.

Phases of evacuation include the detection phase, pre-movement phase, movement phase and evacuation phase, which combined contribute to RSET.

IFEG sub-system F - Fire services (mines rescue) intervention

IFEG Sub-system F provides a framework for the analysis of mines rescue and fire brigade intervention activities.

It addresses the arrival/establishment of mines rescue on site, investigation, set-up, search and rescue, fire attack, fire control and fire extinguishment.

An important aspect of the use of VBFD in mining is that it provides almost immediate fire detection. More importantly for mines rescue activities, it also provides current status of the occupants within the mine, or at least the most recently recorded status, perhaps prior to a significant event, which may cause the loss of cameras.

CONCLUSIONS

The significance of this research is apparent from on-site interviews at mines and actual mine observations carried out. Underground coalmines, in relation to the sites visited during the study, do not have adequate fixed plant fire detection and therefore a significant risk to mine occupants and development assets is assumed. The opportunity to improve fire life safety and asset loss control is considered significant using a performance-based solution. The performance-based fire engineering approach is not a 'blanket style' approach, it is specific and targets achieving a quantifiable level of fire risk management.

The most significant foreseen benefits of this research is that it equally and substantially builds upon the body of knowledge of both fire engineering and mining engineering. It does this by using the IFEG as a tool for managing and guiding mining fire risk analysis and the analysis of trial solutions, such as VBFD.

In more detail, four tentative conclusions are drawn:

- In relation to fire engineering, the research addresses one of the most onerous fire detection situations likely to be encountered. Based on the proof of concept trials undertaken to date, VBFD may be a solution for effective fire detection in underground mines.
- In relation to mining engineering, the IFEG tool specifically addresses mine occupant fire life safety and asset loss control in relation to plant and equipment fires - an area scarcely addressed in previous research. VBFD offers the ability to improve the ASET within a mine under fire conditions, so offers the ability for mines rescue to take earlier action and more informed action during intervention procedures.
- Neither fire engineering research applied to mining, or mining engineering research addressing early fire detection of fixed plant mining systems, has been previously robustly researched. This approach to fire engineering in mines is new, as is the application of VBFD.

- Further research is required involving IFEG assessment of fire scenarios in operating mines. Mines that currently have CCTV cameras fitted should consider carrying out relatively low cost, but high safety gain modifications by enhancing their surveillance and monitoring systems to detect fires.

In terms of future research in the area this ongoing study therefore focuses on a fire detection solution with significantly greater performance under aggressive environmental conditions, which are typically encountered in an underground coalmine.

The next stage of this research is to carry out a range of experiments at SIMTARS in Queensland under simulated mine conditions. Australia does not currently have a suitable test mine location to allow VBFD to be tested under more realistic fire conditions.

These experiments will simulate mine environment conditions including air pollutants, varying light levels and varying air velocity.

Comparative assessment against current gas analysis methods will be undertaken to quantify the performance of VBFD against gas analysis.

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