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MINE SAFETY INSTITUTE OF AUSTRALIA PTY LTD
ABN - 3115 135 4442

Darren Brady
Mine Safety Institute of Australia Pty Ltd
P.O. Box 455
Morningside QLD 4002
Confidential [redacted]

31st December 2015

Mark Bobeldyk
Ventilation Superintendent
Grosvenor Mine
464 Goonyella Road
Moranbah, Qld, 4744

Mark,

Please find the final report relating to the determination of appropriate Spontaneous combustion related TARP triggers for an active longwall. This report replaces the draft report sent 13th October 2015 and includes additional details as discussed in teleconference 9th December 2015.

Please feel free to contact me should you require further information or clarification.

Regards,

[redacted]

Darren Brady

Grosvenor TARP Triggers

Subject: Spontaneous Combustion TARP Triggers

Prepared For: Mark Bobeldyk

Report Date: 31st December 2015

Report By: Darren Brady

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1 Introduction

The Mine Safety Institute of Australia (MSIA) was approached by Grosvenor Mine to provide advice relating to establishing appropriate trigger levels for spontaneous combustion Trigger Action Response Plans (TARPs).

The approach recommended by MSIA and accepted by Grosvenor was initial development of an Active Longwall Spontaneous Combustion TARP based on gas evolution testing and background gas monitoring from Anglo's Moranbah North Mine. Moranbah North is also mining the Goonyella Middle Seam. Applicability of triggers recommended prior to commencement of longwall mining are to be assessed mid block, and recommendations for any changes made based on the data reviewed. Data collected during the mining of the first longwall block will be used to establish TARPs for newly sealed goaves and sealed goaves. Proposed TARPs for newly sealed goaves and sealed goaves will be prepared and provided by a date acceptable and in line with legislative requirement for the application for sealing 30 days before sealing.

Note that this report does not include a review of actions taken at each of the trigger levels, although some comment may be included.

In July 2012 the Chief Inspector sent a letter to all underground coal mine Site Senior Executives and Underground Mine Managers outlining the need for scientific or engineering basis for the determination of TARPs. It was stated in this letter that consideration should be given to retest/validate coal to ensure a full awareness of the chemical properties of the coal and at what temperatures certain gases are liberated and from these effective TARPs could be developed. The letter was prompted following the review of the risk assessment and scientific and/or engineering basis for the determination of different TARP levels at a mine experiencing a heating event. The review found that TARPs were neither adequate or appropriate and the reason for the setting of the TARP levels could not be found.

In March 2014 CB3 Mine Services reported on gas evolution trends associated with laboratory testing of a coal sample from borehole GSC0004 at the Grosvenor mine (CB3 Mine Services Report 2014/TR014). Testing was also conducted by CB3 Mine Services on core samples received from Grosvenor to determine the propensity of the coal to spontaneously combust (CB3 Mine Services Report 2014/TR009). Testing ranked the coal as having low intrinsic spontaneous combustion reactivity, similar to that of Moranbah North. It must be noted however that there have been some oxidation events at Moranbah North that have eventuated in the withdrawal of personnel from the mine.

Generally it is relatively easy to establish what constitutes normal "background" readings by utilising the mine's gas monitoring data; however this information is not available as yet for the Grosvenor operation. Because of the close proximity, mining of the same seam and similarity in laboratory testing, where required, data from the nearby Moranbah North Mine has been utilised. Unless a mine has had a spontaneous combustion event, determination of appropriate trigger levels above what is normal is not as easy from existing data. Even in a mine that has had oxidation events, rarely is it known what temperatures the coal got to. This makes evaluation of the level of risk difficult based on this information alone. For this reason there is a reliance on the laboratory generated gas evolution results for setting triggers for elevated alarm levels.

MDG1006- Spontaneous Combustion Management Guideline (2011), recommends that indicators of spontaneous combustion should include both gas analysis based indicators and other sensory or observation based indicators. These are to be used as input to the mine◌s evaluation/decision process in the development of trigger levels. MDG1006 also states that TARP◌s should be developed with responses to indicators with levels ranging from early detection through to evacuation of the mine and that TARP◌s should define the trigger which will invoke the operation of the incident management team (IMT) to manage spontaneous combustion events. It must be noted that the same IMT that would form during an emergency situation may not be the appropriate team to form to deal with the onset of a spontaneous combustion event. The formation of a spontaneous combustion management team represented by appropriately skilled personnel is considered more appropriate.

The development of a useful TARP requires the early identification of a problem with sufficient time to treat or control the problem before reaching a point where an unacceptable level of risk is reached and underground personnel need to be withdrawn. MDG1006 suggests that Spontaneous combustion TARPs should contain at least three levels:

- A change from the normal conditions requiring investigation
- Evidence of a loss of control requiring action to correct
- A risk of harm to people requiring withdrawal of persons from the area.

It is also recognised that TARPs need to be simple to use and interpret and independent of a particular persons experience or judgement. They should be summarised in one or two pages so as information can be referenced quickly. This summarisation and simplicity should not be at the cost of ambiguity or lead to misinterpretation.

The response depends on the severity of the trigger, if there is the potential for harm to people then the action should be to withdraw people from the area before confirming results. If there is no immediate risk to people confirmation of the results may be warranted action taken.

2 Executive Summary

Recommended spontaneous combustion TARP trigger values are tabulated below and are based on a previous review of Moranbah North data to establish normal levels and gas evolution testing conducted by CB3 Mine Services on a coal sample from Grosvenor and testing by Simtars on coal samples from Moranbah North.

A general approach was applied to setting TARP levels, being that Level 1 was above normal, Level 2 was triggered at around 60^{o}C and Level 3 at approximately 100^{o}C. This gives a conservative approach as far as an ignition source goes but large scale testing shows exponential increases in temperature once the coal reaches 100^{o}C leaving little time to take action.

Recommended Spontaneous Combustion Trigger Levels Active Goaf

SPONTANEOUS COMBUSTION IN ACTIVE GOAF – TRIGGER ACTION RESPONSE PLAN 1				
Level	**Normal**	**Level 1 Response**	**Level 2 Response**	**Level 3 Response**
Longwall Return	CO Make < 30l/min AND Graham's Ratio < 0.3 AND $CO/CO_2 < 0.2$ AND No Ethylene	30l/min ≤ CO Make < 50 l/ min OR 0.3 ≤ Graham's Ratio < 0.5 OR $CO/CO_2 > 0.2$ OR Slowed Production * (To be quantified by Grosvenor)	50l/min ≤ CO Make < 150 l/ min OR 0.5 ≤ Graham's Ratio <1 OR 0ppm < Ethylene < 1ppm OR > 1ppm but CO Make < 50l/min OR Sweating, smell, heat or haze (confirmed by ERZ Controller)	CO Make ≥ 150l/min OR Graham's Ratio ≥ 1 OR Ethylene ≥ 1ppm AND CO Make ≥ 50l/min OR Smoke (coming from goaf)
Goaf Stream	CO < 100ppm AND Graham's Ratio < 0.3 AND No Ethylene	100ppm ≤ CO < 200ppm OR 0.3 ≤ Graham's Ratio < 0.5	200ppm ≤ CO < 800ppm OR 0.5 ≤ Graham's Ratio <1 OR 0ppm < Ethylene <1ppm OR >1ppm but CO <200ppm OR Sweating, smell, heat or haze (confirmed by ERZ Controller)	CO ≥ 800ppm OR Graham's Ratio ≥ 1 OR Ethylene ≥ 1ppm AND CO ≥ 200ppm OR Smoke (coming from goaf)
Active Goaf Seal	CO < 100ppm AND Graham's Ratio < 0.3 AND No Ethylene	100ppm ≤ CO < 200ppm OR 0.3 ≤ Graham's Ratio < 0.5	200ppm ≤CO < 800ppm OR 0.5 ≤ Graham's Ratio < 1 OR 0ppm < Ethylene < 1ppm OR > 1ppm but CO < 200ppm OR Sweating, smell, heat or haze (confirmed by ERZ Controller)	CO ≥ 800ppm OR Graham's Ratio ≥ 1 OR Ethylene ≥ 1ppm AND CO ≥ 200ppm OR Smoke (coming from goaf)

* It is possible that dependent on the monitoring regime (including tube bundle) established and implemented by Grosvenor that this trigger may not be required as discussed further in the body of the report.

3 Discussion

Normally reviewing existing data allows the setting of appropriate normal thresholds giving maximum time to identify and deal with a situation. Because longwall mining is about to be introduced at Grosvenor this data is not available so data from Moranbah North has been used for this purpose. Although it is expected that this will provide reliable information for setting limits for normal indicator parameters, it is recommended that particular attention is paid to results and results and trends evaluated other than just by comparison to recommended triggers. A formal midblock review is also recommended.

It must be noted that initially indicators may be much lower than recommended upper limits for normal but then show increasing trends. This can be typical for the start-up of a longwall as reported by Moreby (2005) and shown in Figure 1. This has been observed elsewhere as well but generally after about 150-200m levels out if no elevated oxidation is occurring.

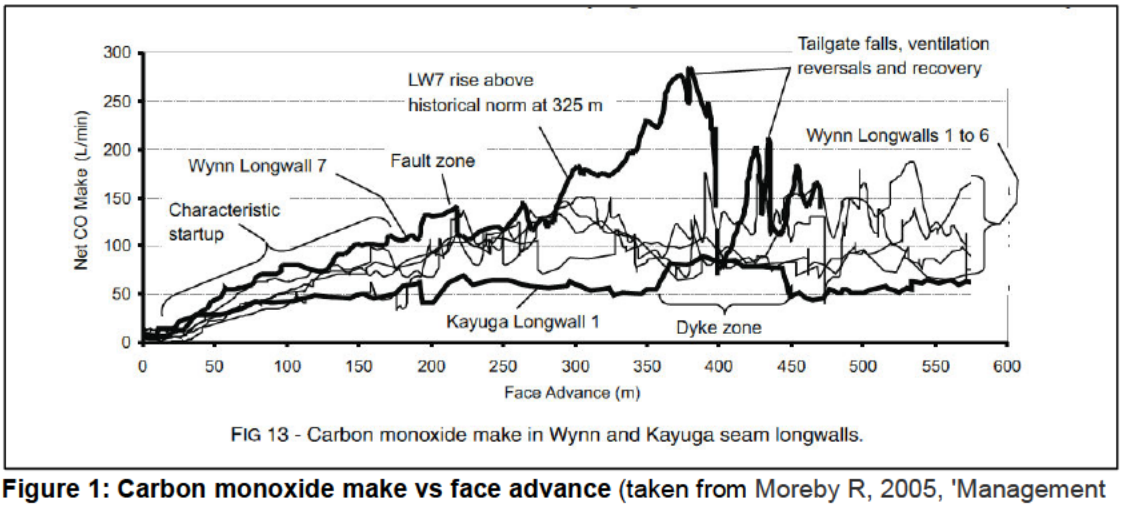

Figure 1: Carbon monoxide make vs face advance (taken from Moreby R, 2005, 'Management of seam gas emission and spontaneous combustion in a highly gassy, thick and multi seam coal mine - A learning experience', in *Australasian Institute of Mining and Metallurgy Publication Series*, pp. 221 – 230)

MDG1006 suggests that Spontaneous combustion TARPs should contain at least three levels:

- A change from the normal conditions requiring investigation
- Evidence of a loss of control requiring action to correct
- A risk of harm to people requiring withdrawal of persons from the area.

This is very similar to that proposed by the Moura No. 2 Task Group 2:

- The collection of additional data to ascertain a course of action
- The initiation of Action Response Plans
- The withdrawal of persons to a place of safety.

When an explosive gas mixture could be or is present, spontaneous combustion that has progressed to a potential ignition source must initiate the withdrawal of persons from underground (with a conservative approach to when withdrawal is initiated) in line with the third trigger level recommended in MDG1006. Based on knowledge of other mining operations in the area, it would appear that it is likely that an explosive atmosphere will or could exist in a longwall block at Grosvenor. These explosive mixtures are typical of mining a seam with methane seam gas and can occur as the goaf self inerts and passes from essentially fresh air through to being fuel rich. Typical places are maingate seals and at a fringe behind the longwall supports.

Requiring an explosive mixture to be present as well as an ignition source to trigger a Level 3 response introduces significant difficulties. In particular is the association of the explosive mixture and spontaneous combustion indicator. For example a tailgate return sample could indicate that an ignition source exists in the goaf, but it would be unlikely for that particular sample to be explosive. Explosibility of that sample is not representative of the risk. External factors come into consideration such as possibility of a roof fall that could push an explosive mixture over the ignition source or as described in the Kianga Warden's Inquiry report, a barometric pressure low could move an explosive mixture forward over the ignition source. By assuming that an explosive mixture exists the TARPs become much more effective and easier to apply. Should the circumstance arise that a withdrawal has occurred but an explosive mixture doesn't and cannot form, a risk management process can be applied to return underground, but during a time everyone is in a place of safety.

When determining appropriate Level 3 triggers to recommend, consideration was given to the rate at which spontaneous combustion activity can progress. As seen in Figure 2, large scale testing of various coals by Simtars showed that the rate of oxidation could increase exponentially once temperatures exceed 100°C. Similarly exponential increases in carbon monoxide are seen with the increase in temperature. The data collected from the 512 Panel at Moura prior to the explosion also shows the rapid onset of an exponential increase in carbon monoxide. Based on this recommended Level 3 triggers are aligned to a coal temperature of 100°C.

Setting level 3 Triggers conservatively to match indicators expected at 100°C minimises the chances of an exponential increase in temperature while workers remain underground. This is the most critical trigger level to set correctly as it needs to remove persons from the mine before an unacceptable level of risk exists. Using 100°C allows a significant safety margin in relation to the spontaneous combustion event being an ignition source (Matheson Gas Data Handbook reports ignition temperature of methane to be 537°C).

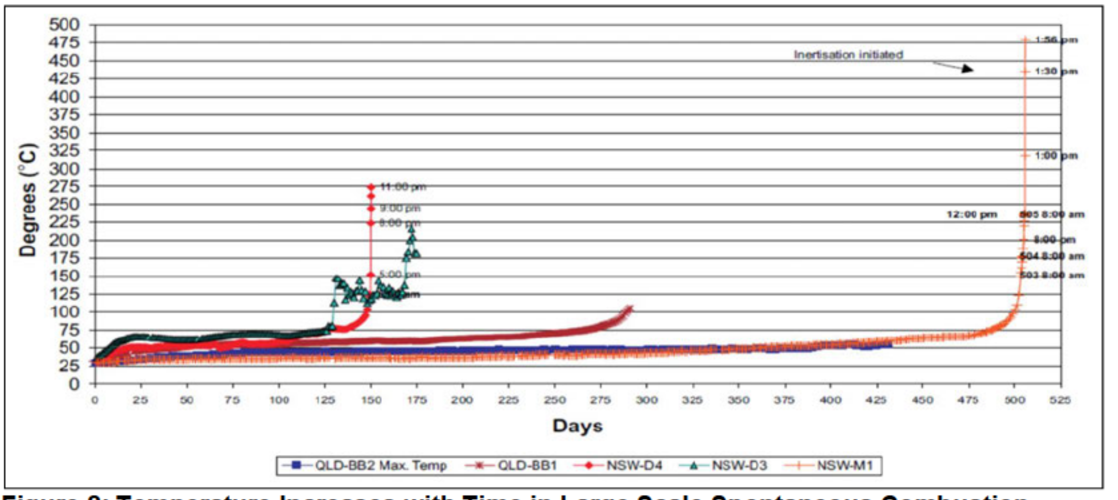

Figure 2: Temperature Increases with Time in Large Scale Spontaneous Combustion Testing

Establishing what constituents a normal value is important in determining when an abnormal state has been reached. This allows actions to be taken to confirm situation and to start implementing controls. A balance is required in setting the triggers so that alerted to an abnormal situation but not too sensitive so as to be generating what are perceived as nuisance alarms. Reviewing existing data allows for the reliable identification of a range of values that are what can be considered normal with no evidence of increasing oxidation rates.

The lower Level 1 Trigger is based on what is above the expected normal range. Generally Level 1 Triggers instigate checking and confirmation of results/situation, often with increased sampling regimes but few mitigating controls introduced. For this reason the range suggested in this review is narrow and once an abnormal situation is identified actions should be commenced to take control. The upper limit of this level obviously matches the lower Level 2 Trigger.

Most controls are implemented in the Level 2 range, although there is no reason to wait until the situation escalates before implementing controls once it is confirmed that results are outside of what is normal. With a starting temperature of around 40°C and 100°C set as the Level 3 Trigger (which matches the upper Level 2 limit), the Level 2 is most appropriately set up as between 60°C and 100°C. This means setting the Level 1 upper trigger to also match a temperature ~60°C. Table 1 outlines the target temperature range for each trigger level.

Table 1: Target Trigger Level Temperatures

Normal	Level 1	Level 2	Level 3
up to 45°C	45-60°C	60-100°C	>100°C

Level 1 and 2 Triggers are about identifying if something isn't normal and implementing controls to gain control and checks to make sure controls are being effective. The need for AND statements at these levels are questionable and not recommended. They can lead to issues where gas results technically don't fit into any trigger level because one of the requirements is in one level and the other at a lower level. An example would be if triggers for carbon monoxide and hydrogen were required to initiate a trigger, the carbon monoxide might meet Level 2 requirements but the hydrogen may only be at Level 1 so the sample doesn't technically match either trigger level although signifying a significant event.

For these reasons it is recommended that AND statements are not used in Level 1 and Level 2 conditions. The use of AND statements in Level 3 Triggers are addressed in more detail for individual parameters and sample locations in the recommended trigger levels section of this report. It must be remembered that Level 3 represents an unacceptable level of risk so the implication of AND statements must be considered relating to this evaluation. The use of the term increasing is not recommended for use in TARPs particularly for Level 3. Level 3 represent a situation determined to present an unacceptable level of risk and requires the withdrawal of personnel. Having a trigger that requires that this predetermined condition actually gets worse before withdrawal is not in line with good risk management principles.

The Warden's report on the Moura No. 2 explosion included "There was no protocol at Moura No 2 for the withdrawal of persons from the mine in response to potential dangers. This left consideration of questions of withdrawal to those officials who happened to be on duty at any particular time. In the actual event the question of withdrawal was immersed in uncertainties with regard to the state of the mine and, in any case, appeared to have been left largely to the opinion of the middle ranking official who happened to be on duty. Any attempts that official made to obtain guidance from more senior management were not fruitful and, ultimately, any question of staying out of the mine was left to the workforce. This situation is totally unacceptable."

It is strongly recommended that any Level 3 Triggers are clear and require no interpreting or opinion on what is required to satisfy the condition.

There is often a desire to include multiple parameters before triggering a Level 3 response. This can result in delays in withdrawal when significant evidence exists supporting that an unacceptable level of risk has been reached. Systems and maintenance should already be in place to ensure that the monitoring systems are operating in a manner to ensure generated results are accurate and representative.

In relation to spontaneous combustion the Coal Mining Safety and Health Regulation 2001, Chapter 4 Underground mines, Part 7 Gas Monitoring requires the gas monitoring system to detect carbon monoxide, carbon dioxide and oxygen and to calculate the ratio of carbon monoxide and oxygen deficiency (Graham's ratio) and the ratio of carbon monoxide and carbon dioxide. An alarm is to be activated if a gas alarm level is exceeded. Most mines also utilises CO Make in their TARPs as an indicator of spontaneous combustion. Advantages of CO Make over raw carbon monoxide were identified and discussed in the Kianga Warden's report and the Moura No. 2 Warden's report.

Although required by legislation the ratio of carbon monoxide and carbon dioxide at Grosvenor may not be a reliable indicator as the ratio assumes all of the carbon dioxide present to be product from combustion. The setting of a meaningful trigger is totally reliant on the seam gas contribution of the carbon dioxide concentration. MSIA has been advised that the seam gas ratio of methane to carbon dioxide in core samples from LW101 is 95:5. Experience at many of the mines in the Bowen Basin is that because of carbon dioxide content in the seam gas the ratio is not reliable. Variables such as cutting rate and barometric pressure influence the amount of carbon dioxide in returns influencing the magnitude of the ratio making it a varying and therefore unreliable parameter. Although it should not be dismissed alltogether as an interpretative tool further work is required to determine its suitability as a trigger at all levels in the TARPs.

Many of the parameters being monitored are reliant on the same variable or at least significantly influenced by it. In a longwall return CO Make and Grahamôs ratio are mainly influenced by the carbon moxide concentration. It is important that the respective trigger levels ñmatchò.

As reported by Professor David Cliff in a paper titled Trigger Action Response Plans (TARPs) in Underground Coal Mines - Tips, Tricks and Pitfalls he authored ñWhen setting triggers it is important to define which of the mine monitoring systems is to be used as the reference to decide the trigger has been reached. Portable handheld monitors are not designed to be precision gas monitors. Both tube bundle systems and gas chromatographs can be very accurate but they need to be calibrated in the concentration ranges of interest. There have been many examples of a trigger being reached when a sample is analysed on the GC and not on the tube bundle system, due to inadequate calibration ï dual range infrared analysers may require twelve calibration points to ensure linearity across both ranges. This takes time (and costs money) so there may be a tendency to not do the complete calibration. It is not going to generate confidence in mine management if the workforce hears that even though the trigger to evacuate has been reached on one system it is safe to be underground because the other system says it has not been reached.ò

Although Professor Cliff has indicated that gas chromatographs can be very accurate, there are common problems associated with determining oxygen deficiency using this technique when the oxygen to nitrogen ratio is close to fresh air such as in a longwall return. This technique is also not the most appropriate for determining low carbon monoxide concentrations accurately (less than 5ppm). This coupled with more frequent analysis makes the use of a properly calibrated and maintained tube bundle system the preferred technique for determining raw carbon monoxide concentration, CO make, Grahamôs ratio and the ratio of carbon monoxide to carbon dioxide in longwall returns (although legislation would indicate that this also needs to be done using the real time system for all but CO Make).

The gas chromatograph (GC) is a suitable technique for analysing bag samples from the goaf stream, behind active goaf seals, sealed goaves, or anywhere samples are collected to determine the presence of ethylene or hydrogen. The goaf stream is a good place to take samples for subsequent GC analysis as it is not diluted by the air travelling across the face and as such is more likely to contain any indicators at higher concentrations than in the tailgate. Samples collected in the tailgate are diluted by the full ventilation quantity. Hydrogen is not recommended as a trigger in any of the TARPs but this does not mean that trending and use of hydrogen in interpretation of results is not useful, but not including it simplifies TARPs. It is well known now that hydrogen exists even in the absence of elevated temperatures, and its concentration can vary significantly dependent on sample location, making the setting of triggers somewhat unreliable.

It is difficult to cover every possibility in a TARP and still keep it simple (simplicity must be a priority). Therefore basic situations are covered with a conservative approach. It is readily foreseeable that a situation may arise that triggers the evacuation of the mine, at which time a review of the data and situation can be made to determine the level of risk, whilst workers are on the surface in a place of safety. This does mean however that the triggers used to withdraw workers donọt necessarily apply as the same values for re-entry TARPs. These need to be determined based on particular scenarios/situations.

TARPs are a means of ensuring that actions are implemented dependent on concentrations measured but should be used in conjunction with regular review and interpretation of gas results and not as the sole interpretation tool. For example it is unlikely that a mine would introduce an oxygen trigger for seal samples in an active goaf (too difficult considering it would be dependent on too many factors and would be starting at 20.9%), however if oxygen does not show signs of decreasing as the longwall retreats outbye then investigation is warranted.

3.1 Spontaneous Combustion Testing

A limitation of laboratory testing is that the absolute concentrations of gases determined at various coal temperatures cannot be directly transferred to TARP levels. This is because they are based on the amount of coal and the flow rate used in the testing. Instead ratios of gases and appearance temperatures are utilised.

Grosvenor had a sample from Borehole GSC0004 tested for gas evolution by CB3 Mine Services in 2014 (Report 2014/TR014). Because Grosvenor has no background data to use to assist in setting trigger levels and data from Moranbah North is being used where appropriate, gas evolution data from Moranbah North is also being considered in this report. Spontaneous combustion propensity testing conducted by CB3 Mining Services (Report 2014/TR0009) identified the propensity of the Grosvenor sample as being similar to that of Moranbah North.

Gas evolution testing of Moranbah North Coal has been conducted by Simtars rather than CB3 Mining Services. The most recent testing was in 2012 and detailed in Simtars Report OG420206F2. Previous testing had been performed in 2005 and 2003. Results for all tests were displayed graphically in Simtars Report OG420206F2 with those most relevant included as Figure 3 - Figure 7 below. As can be seen results from all tests showed close alignment.

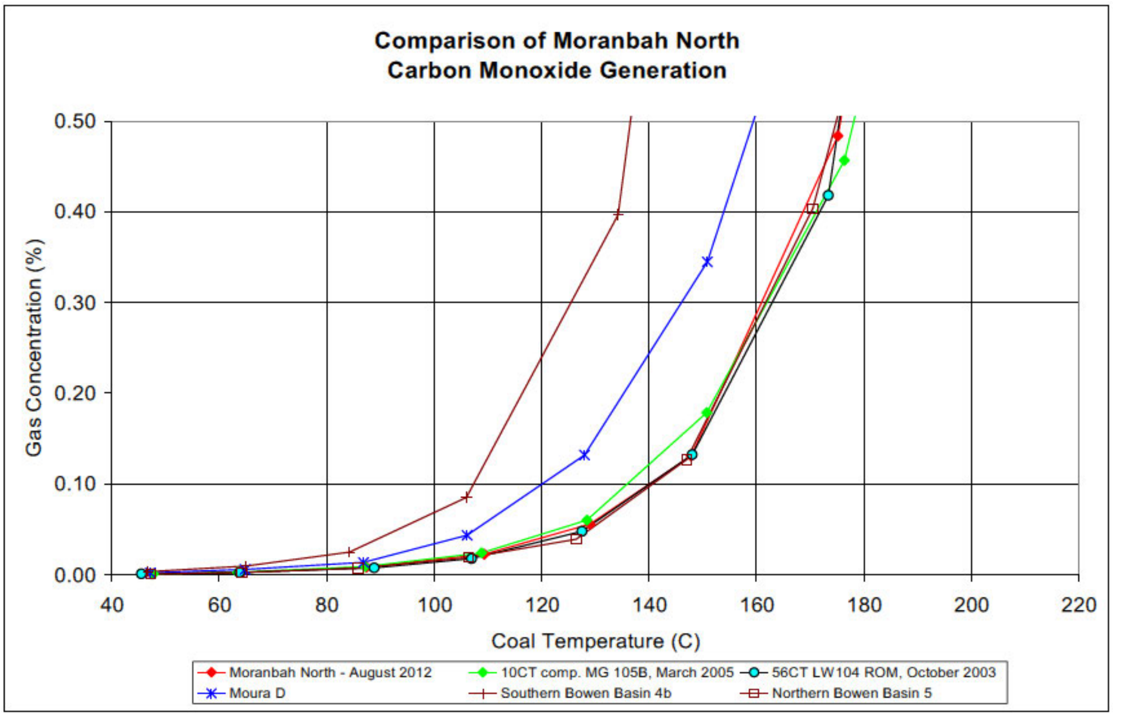

Figure 3: Moranbah North carbon monoxide evolution

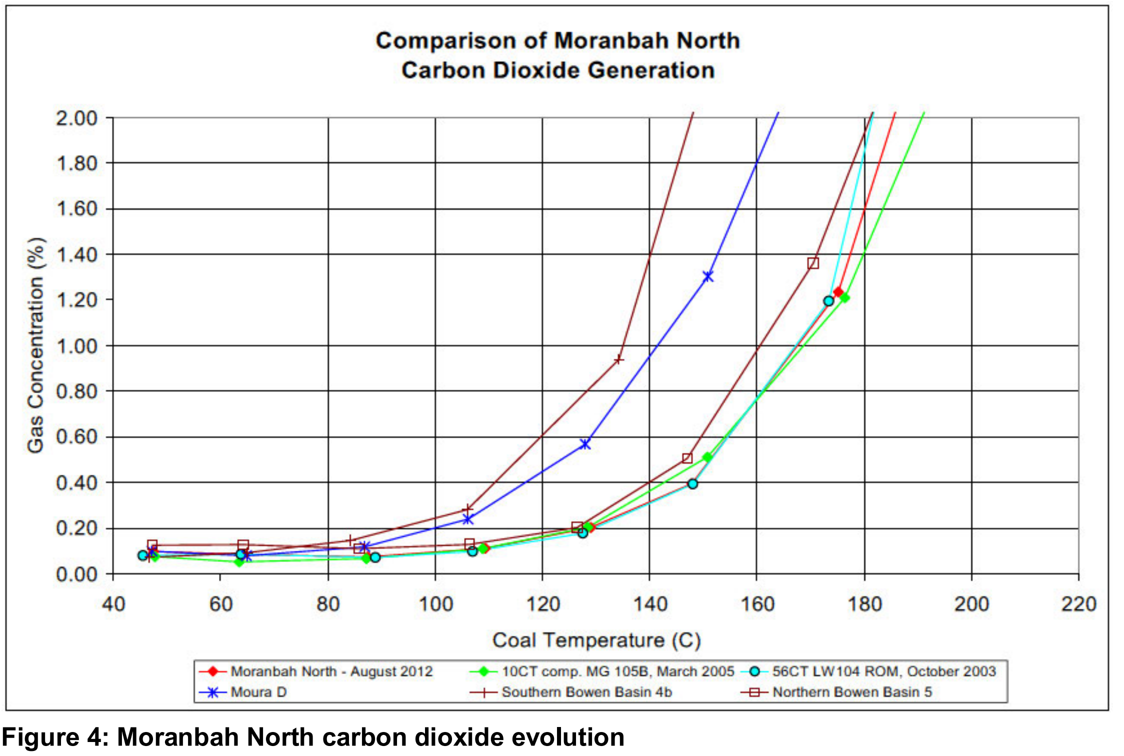

Figure 4: Moranbah North carbon dioxide evolution

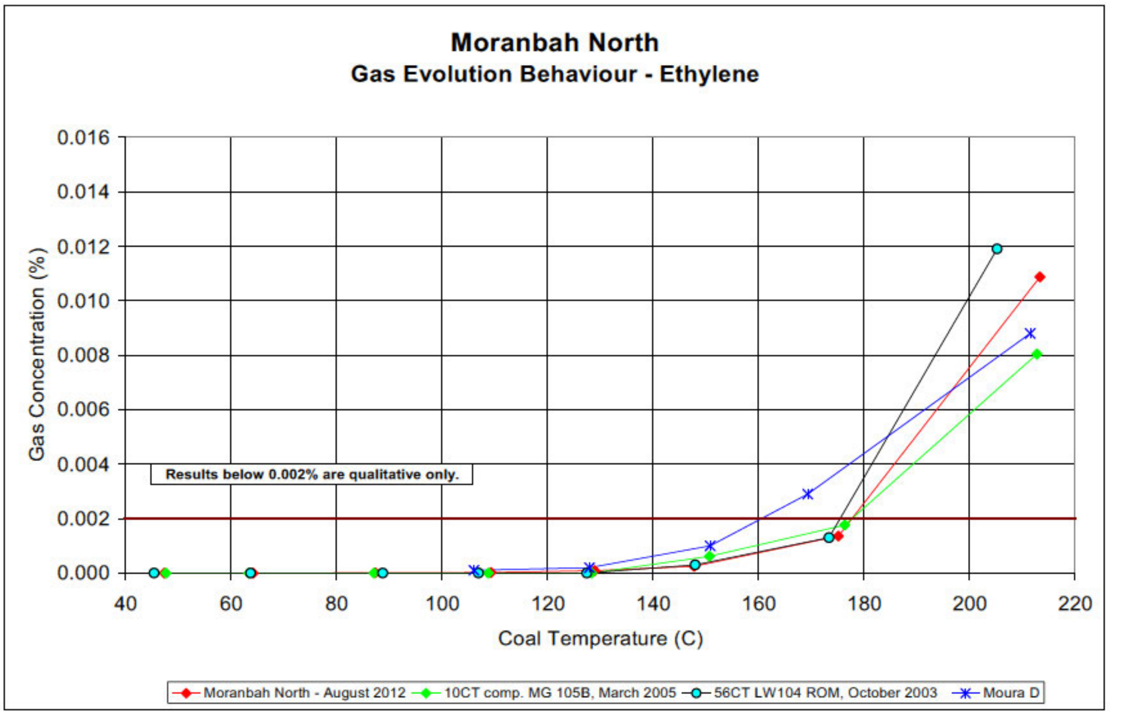

Figure 5: Moranbah North ethylene evolution

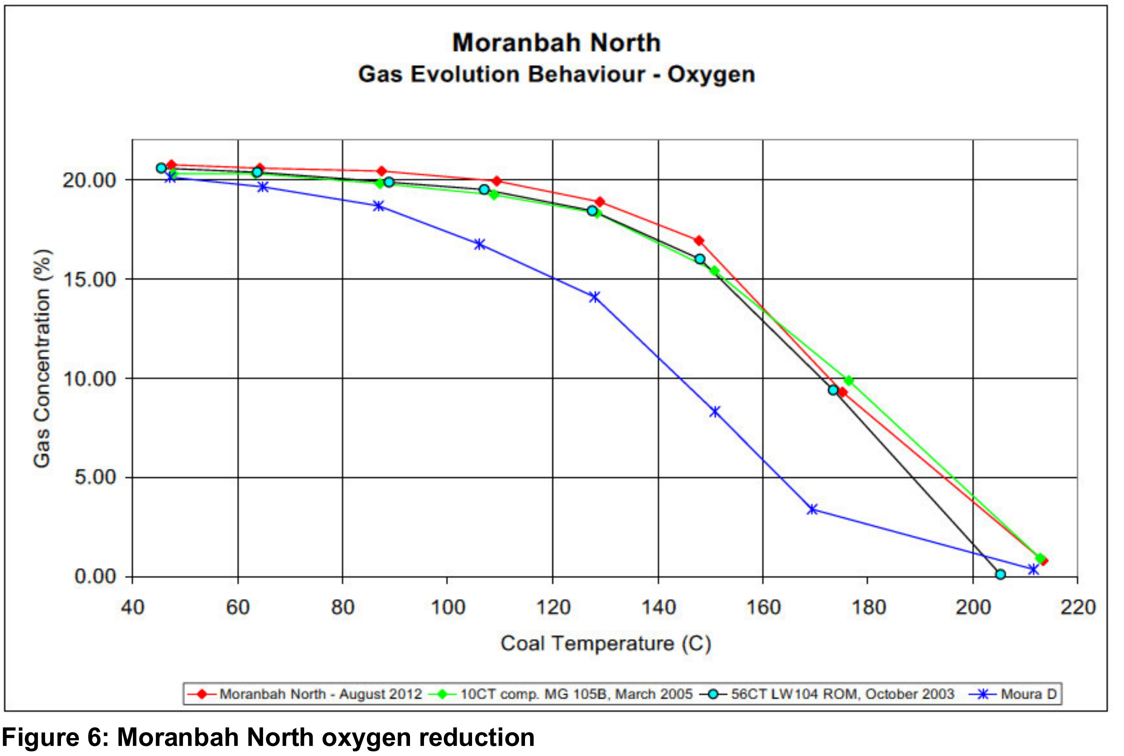

Figure 6: Moranbah North oxygen reduction

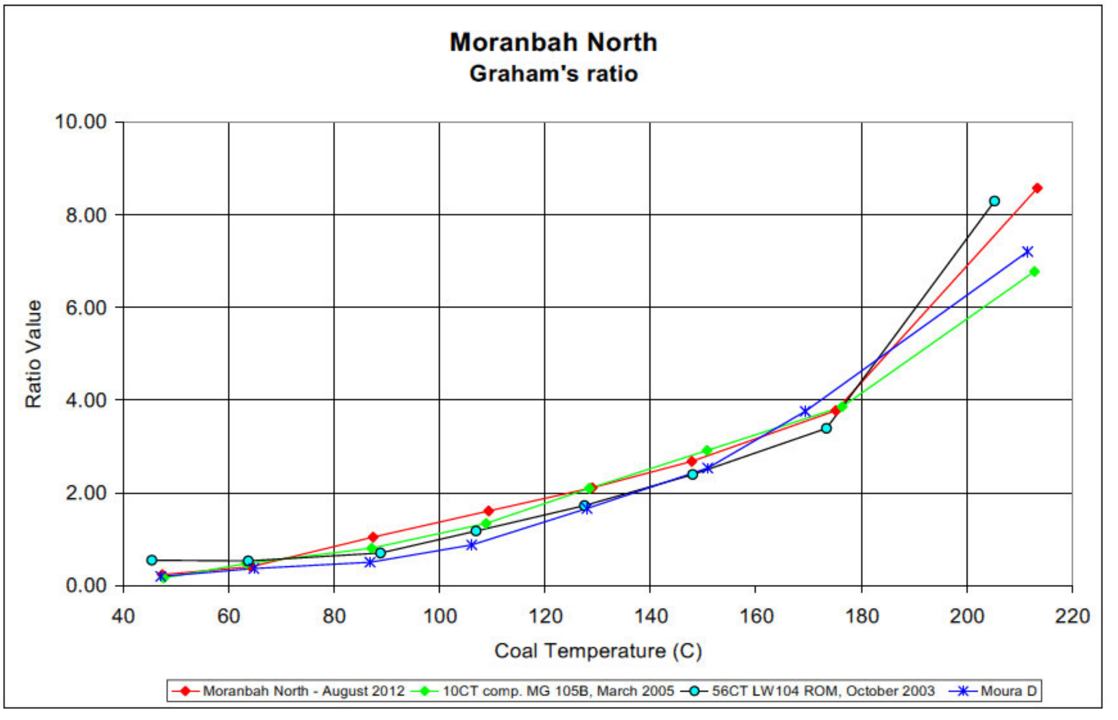

Figure 7: Moranbah North Graham's ratio

Raw results are available for the August 2012 testing and as such these have been used for comparison with the Grosvenor sample. Although the other samples have not been included for direct comparison the similarity between results shown in Figure 3 - Figure 7 justifies comparison with just the one sample. Table 2 summarises the results from testing of the Grosvenor borehole sample and the most recent Moranbah North sample. Graphical display of data is shown in Figure 8 - Figure 21.

Testing conducted by CB3 Mine Services Pty Ltd used 150 grams of coal sample milled to less than 212µm. Dry air was passed through the sample at 10cm^3/min. Gas samples were obtained as the coal was heated in the oven. The samples were subsequently analysed by gas chromatography. Coal was heated to a maximum of approximately 190^{o}C.

The testing conducted by Simtars used approximately 70 grams of coal milled to minus 250µm. Wet air was flowed through the test vessel at approximately 60cm^3/min. The coal was heated in 20^{o}C steps to approximately 160^{o}C and then a 40^{o}C step to 200^{o}C at 0.4^{o}C per minute.

On its own the additional coal (more than twice) used in the CB3 testing could result in more products of combustion being produced, simply because there is more product to react. Of more significance is the difference in the amount of air used by the two laboratories. The much lower flow rate used by CB3 influences the oxygen available to react with the coal. This will be magnified due to the extra coal used in CB3 testing. It is difficult to quantify the influence dry air has over wet air. Dry air passing through the coal is likely to remove water from the coal which has a cooling effect but also opens pores for subsequent reaction with oxygen. Wet air can have the opposite effect, with deposition of water warming the coal but "blocking" active sites for reaction with oxygen, it is a fine balance and actual influence in small scale testing not definitively known.

The differences between these two test methods need to be taken in context when evaluating results for use in setting triggers. Essentially the CB3 tests provide more coal and less oxygen when compared with the Simtars tests. The additional coal is not an issue on its own as absolute concentrations cannot be used for reasons already identified, so ratios become a valuable tool. The measure of conversion efficiency and therefore temperature by how much carbon monoxide is produced for how much oxygen is consumed, still stands, so long as there is enough oxygen available for the oxidation reaction to proceed without a bias towards production of carbon monoxide over carbon dioxide. The higher concentrations of carbon monoxide at the start temperature generated by the CB3 testing have been observed for other mines using this laboratory for testing.

Figure 10 shows the calculated oxygen deficiency for each temperature. Up to 100^{o}C oxygen is still available but as the temperature increases the oxygen deficiency does as well and as can be seen once temperature is close to 200^{o}C most of the oxygen is consumed. Because there is oxygen available at 100^{o}C the approach of aligning Level 3 Triggers with 100^{o}C means that the parameters from laboratory testing results can be used with some confidence up to this temperature. It must be noted that the oxygen deficiency used by both laboratories appears to be based on using the following equation:
Oxygen deficiency = 0.268* measured nitrogen% – measured oxygen%

The initial oxygen concentration is calculated based on the ratio of oxygen to nitrogen in fresh air. As gas chromatography is used for analysis, nitrogen is quantified on its own with no contribution to the value from inerts such as argon. This is not the case with many other techniques where nitrogen is determined by difference and includes inerts. This is why a factor of 0.268 is used rather than the commonly seen 0.265. Use of this equation does however introduce problems as a result of the loss of oxygen either adsorbed into the coal or converted to water (which is not analysed) in the reaction. This results in the measured nitrogen concentration being greater than that of fresh air and when the factor is applied an initial oxygen concentration greater than that of fresh air is returned. Figure 19 shows the calculated initial oxygen concentration and as can be seen values increase with temperature and are well above maximum possible values.

The impact of this is that calculated oxygen deficiency values are greater than what they are in reality and as such underestimate ratios such as Graham's that use the value in the denominator of the equation. It is most probable that onsite calculations will be done in the same way so although noted as underestimating Graham's ratio, this calculation is still used. Even if calculated correctly onsite, using underestimated values for determining trigger points is conservative and increases the factor of safety.

Absolute concentrations from testing can't be used because they are dependent on the amount of coal tested and the volume of air supplied. Instead ratios of gases and appearance temperatures are utilised.

Figure 10 and Figure 11 show the factor of increase in carbon monoxide from that measured in the sample collected at about 45^{o}C. As can be seen, the difference between the two samples is minimal up to about 90^{o}C, but after that the Grosvenor sample does not show as a great an increase. This has been observed by the author for gas evolution testing for samples from the same mine but tested by the two different laboratories and is considered to be more dependent on test conditions than the coal itself. Similar observations apply to the factor of increase from carbon monoxide generated at approximately 60^{o}C shown graphically in Figure 12 and Figure 13.

A good measure of intensity of any oxidation event is Graham's ratio as it looks at carbon monoxide produced for oxygen used up. A comparison of both samples can be seen in Figure 20 and over a lower temperature range in Figure 21. There is very good correlation between the two samples between 80 and 180^{o}C. For a new mining technique where mine specific background levels will not be established for some time, Graham's ratio will be a valuable tool in setting trigger levels.

The appearance of ethylene has been used for some time as an indicator of increased intensity of a heating. Gas evolution results for the Moranbah North sample indicate that trace amounts of ethylene (less than 1ppm) were detected initially in the 87^{o}C sample. It wasn't until almost 130^{o}C that 1ppm was detected. For the Grosvenor sample testing, ethylene was first detected at 3ppm in the sample collected at 100^{o}C.

When using the appearance of ethylene as an indicator for spontaneous combustion in a mine the context of laboratory testing must be remembered. All of the "offgas" being generated is collected into a bag and this sample is the most representative that could possibly be collected. This is not the case for samples collected underground. It is highly improbable that any sample collected will be purely the "offgas" from the oxidation activity. It will generally be significantly diluted by other gas streams. For this reason it is not recommended that a Level 3 response require ethylene to be detected before being triggered. Dependent on the location of the oxidation event in relation to the sample point, temperatures well above the ignition temperature of methane may need to be reached before sufficient ethylene is generated to be detected in the collected sample. This is further reasoning for the inclusion of Graham's ratio as a critical trigger as it is not influenced by dilution with seam gas or air.

It was often considered and in fact taught that use of Graham's ratio was restricted to areas where there were airflows and not for use behind seals. Graham's ratio dates back to 1921 and it could be argued that there are now more issues with using the ratio in ventilated areas compared with non-ventilated based on the volume of air and ventilation techniques used in modern mines compared to those in the 1920's. True there are issues with lack of purging of evolved gases behind seals, but use of the ratio in these areas has proved valuable to the author on multiple occasions when responding to oxidation events. For ongoing oxidation to be occurring a source of oxygen is required so there needs to be some flow anyway. If an increase is seen in Graham's ratio it is indicator of increasing coal temperature regardless of any air movement. Because of its usefulness in the past and no valid scientific reason to dismiss increases it is recommended that triggers for Graham's ratio be including for seal monitoring locations.

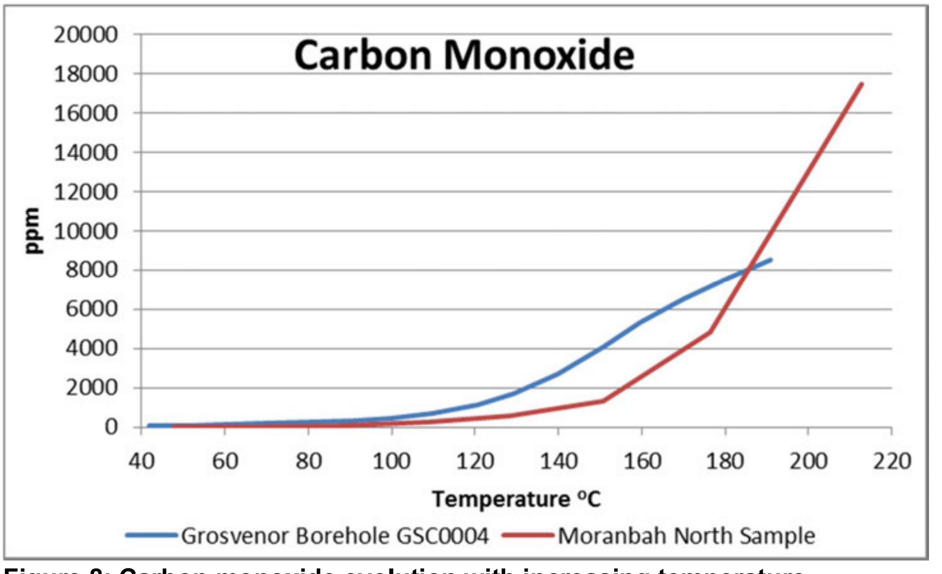

Figure 8: Carbon monoxide evolution with increasing temperature

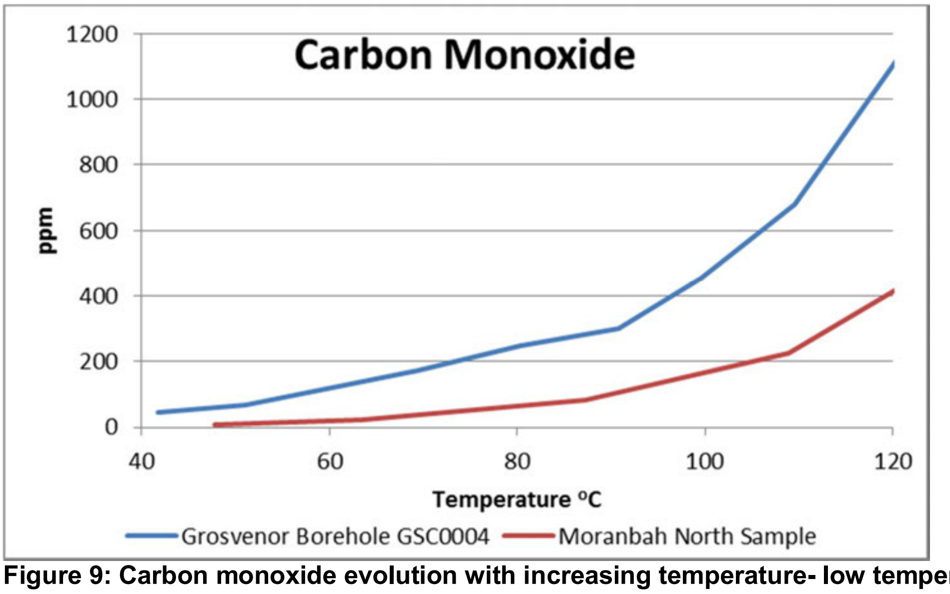

Figure 9: Carbon monoxide evolution with increasing temperature- low temperature range

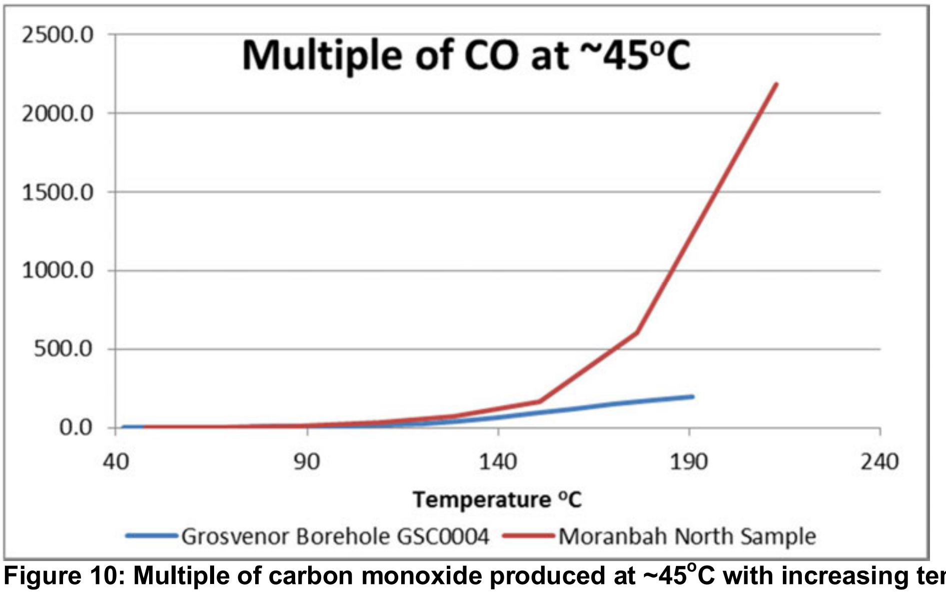

Figure 10: Multiple of carbon monoxide produced at ~45°C with increasing temperature

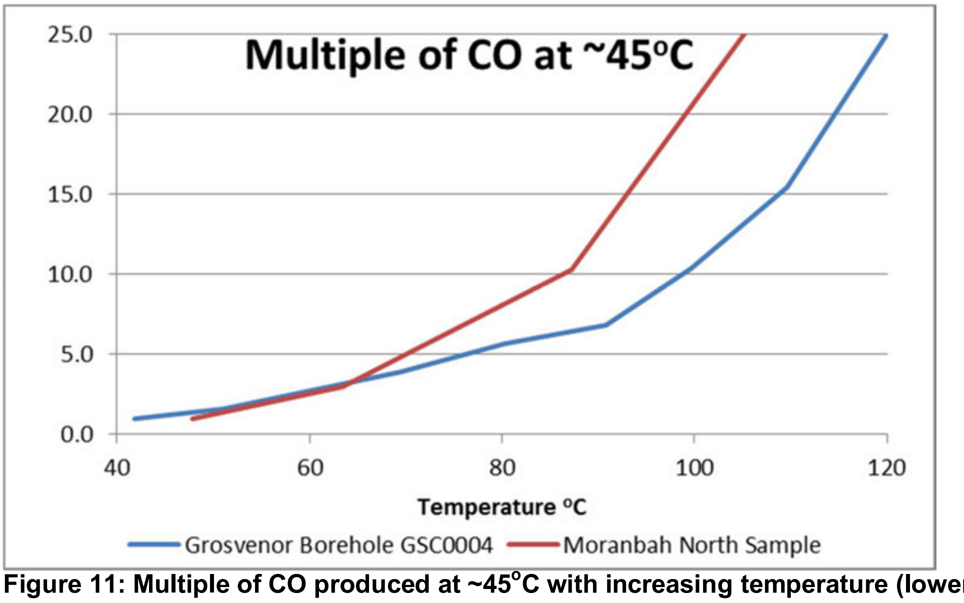

Figure 11: Multiple of CO produced at ~45°C with increasing temperature (lower range)

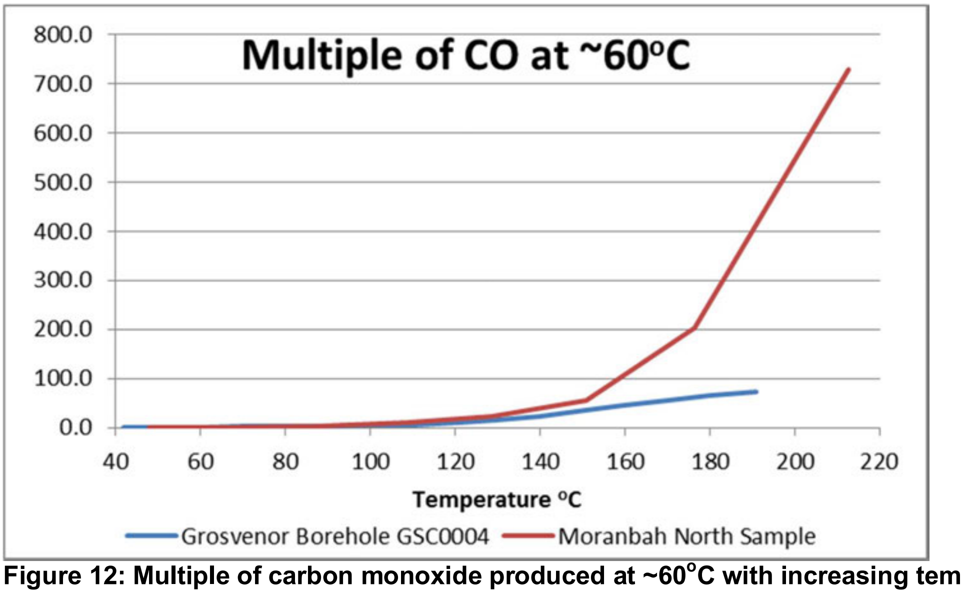

Figure 12: Multiple of carbon monoxide produced at ~60°C with increasing temperature

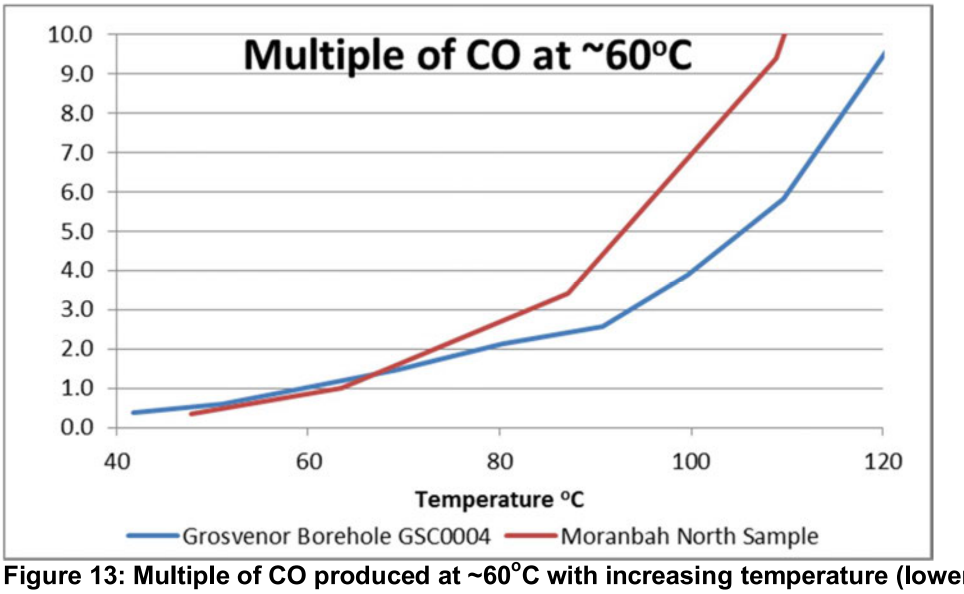

Figure 13: Multiple of CO produced at ~60°C with increasing temperature (lower range)

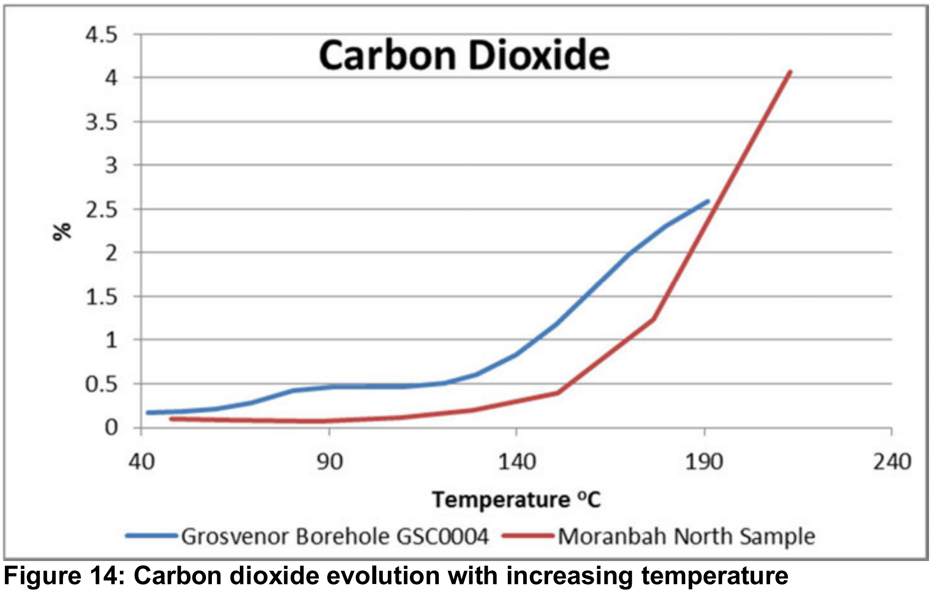

Figure 14: Carbon dioxide evolution with increasing temperature

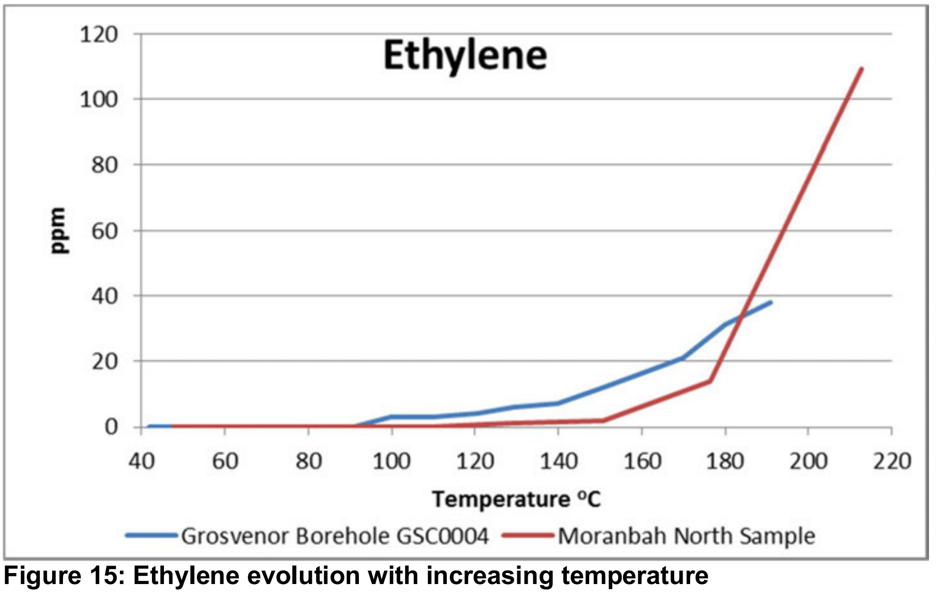

Figure 15: Ethylene evolution with increasing temperature

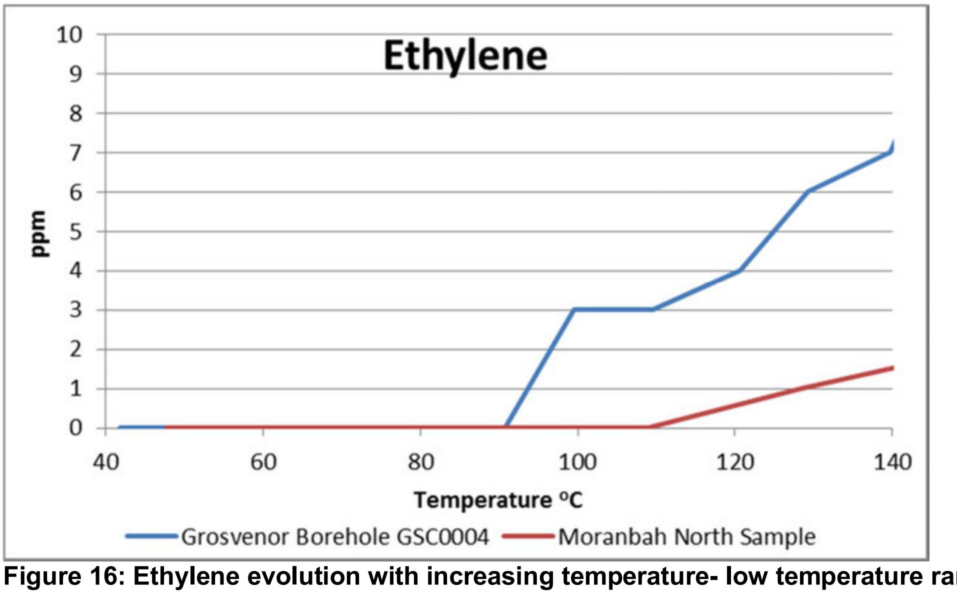

Figure 16: Ethylene evolution with increasing temperature- low temperature range

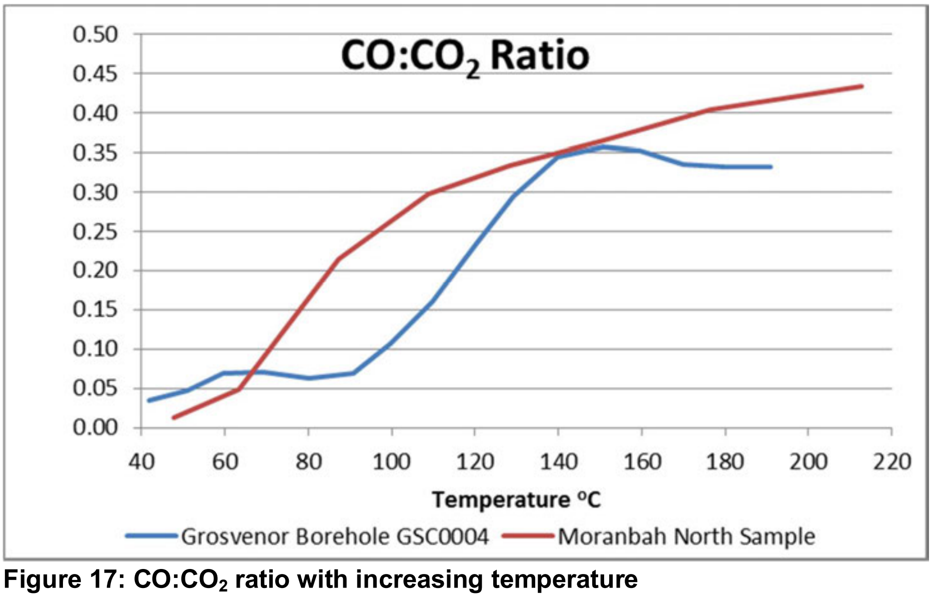

Figure 17: $CO:CO_2$ ratio with increasing temperature

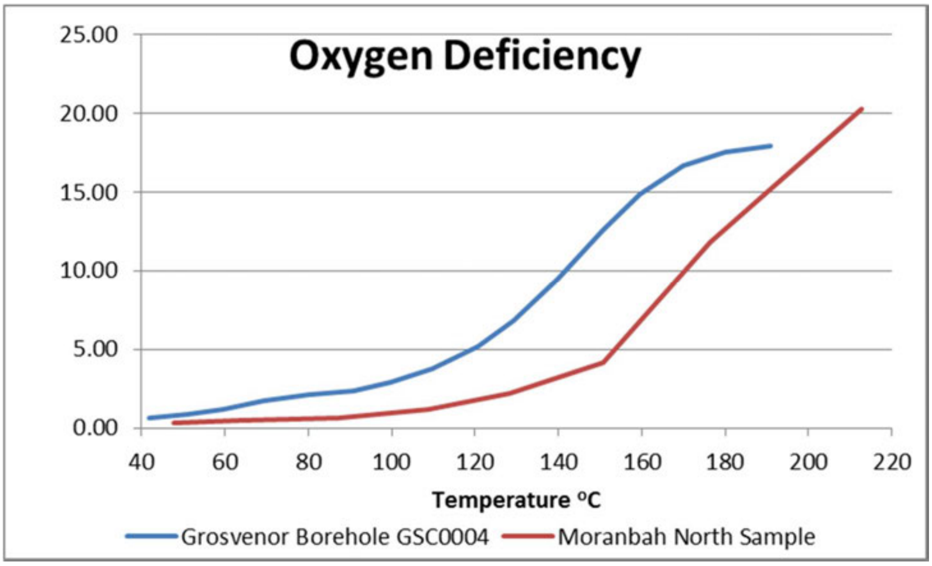

Figure 18: Oxygen Deficiency with increasing temperature

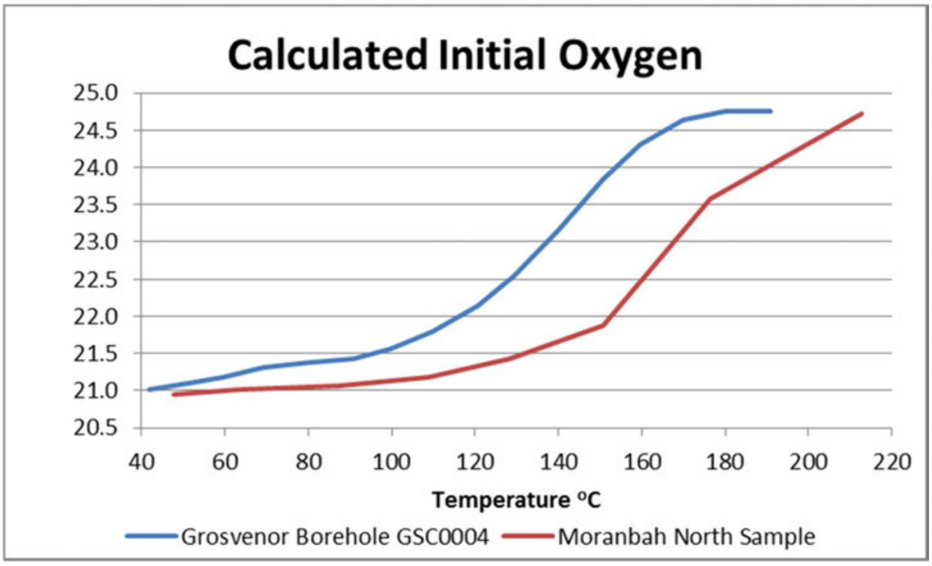

Figure 19: Calculated initial oxygen with increasing temperature

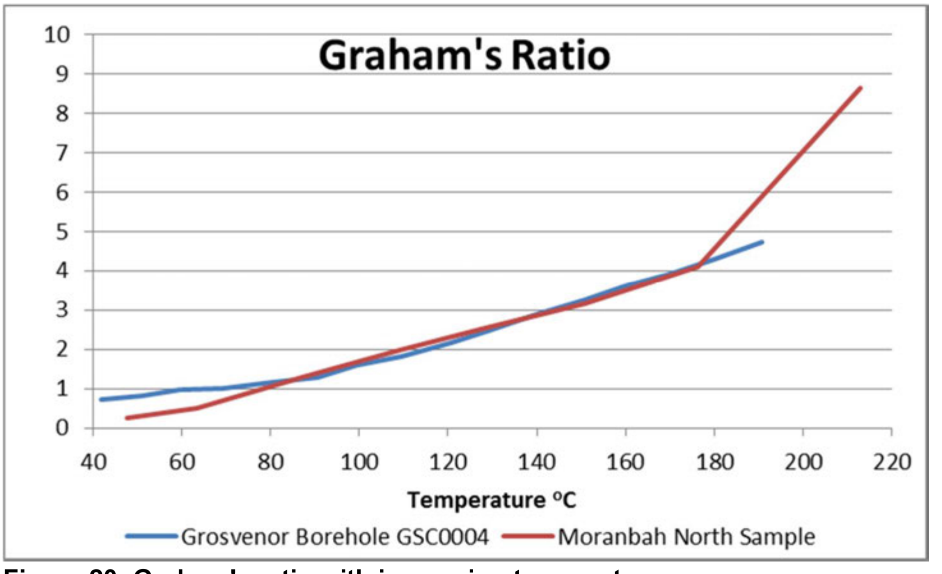

Figure 20: Graham's ratio with increasing temperature

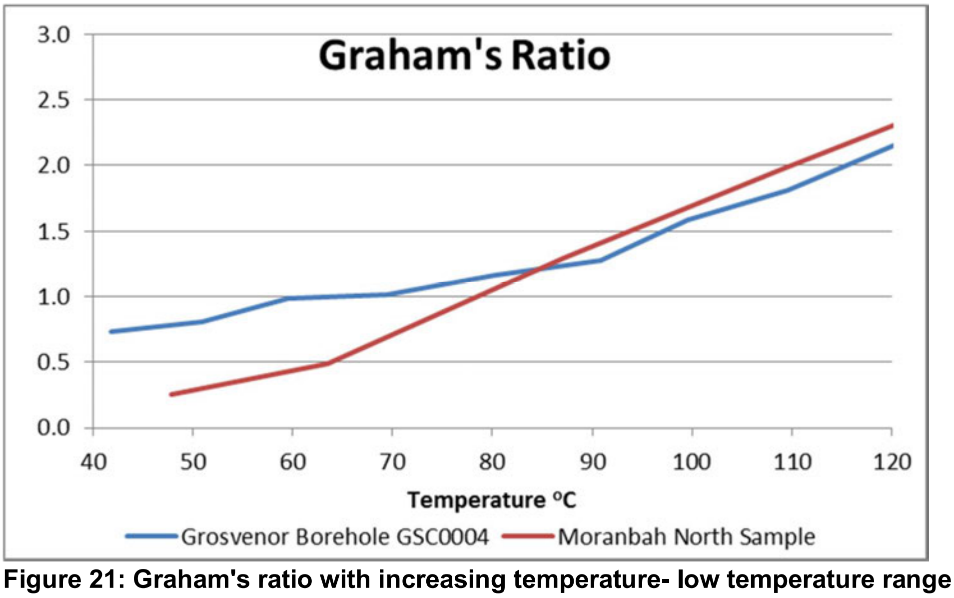

Figure 21: Graham's ratio with increasing temperature- low temperature range

Table 2: Summary of Gas Evolution Testing

Sample	Temp (°C)	Hydrogen (ppm)	Oxygen (%)	Nitrogen (%)	Methane (%)	Carbon Monoxide (ppm)	Carbon Dioxide (%)	Ethylene (ppm)	Ethane (%)	Oxygen Deficiency	Graham's Ratio	CO/CO_2 Ratio	Multiple of CO at 42°C	Multiple of CO at 60°C
Grosvenor Borehole GSC0004 CB3 Testing	41.8	N.D.	20.35	78.40	0.1504	44	0.1627	N.D.	34	0.66	0.67	0.034	1.0	0.4
	51	N.D.	20.09	78.73	0.0469	69	0.1824	N.D.	35	1.00	0.69	0.047	1.6	0.6
	59.6	4	19.76	79.05	0.0272	117	0.2062	N.D.	33	1.43	0.82	0.068	2.7	1.0
	69.4	6	19.24	79.50	0.0198	173	0.2829	N.D.	18	2.07	0.84	0.070	3.9	1.5
	80.3	10	18.82	79.75	0.0153	248	0.4296	N.D.	11	2.55	0.97	0.063	5.6	2.1
	90.8	14	18.59	79.94	0.0135	301	0.4711	N.D.	8	2.84	1.06	0.069	6.8	2.6
	99.6	19	18.09	80.43	0.0124	455	0.4635	3	6	3.47	1.31	0.106	10.3	3.9
	109.6	29	17.20	81.29	0.0134	680	0.4595	3	13	4.58	1.48	0.160	15.5	5.8
	120.6	49	15.76	82.61	0.0143	1127	0.5111	4	14	6.38	1.77	0.237	25.6	9.6
	129.3	69	14.12	84.08	0.0163	1690	0.609	6	22	8.41	2.01	0.294	38.4	14.4
	139.8	102	11.46	86.38	0.0169	2721	0.8259	7	31	11.69	2.33	0.344	61.8	23.3
	150.7	133	8.37	88.95	0.0189	4076	1.1782	12	44	15.47	2.64	0.357	92.6	34.8
	159.6	143	6.11	90.68	0.0225	5330	1.5503	16	58	18.19	2.93	0.352	121.1	45.6
	170	126	4.29	91.94	0.0237	6503	1.9779	21	82	20 35	3.20	0.335	147.8	55.6
	179.9	101	3.41	92.38	0.0265	7526	2.309	31	97	21 35	3.53	0.331	171.0	64.3
	190.8	77	3.05	92.35	0.0294	8475	2.5915	38	105	21.70	3.91	0.332	192.6	72.4
Moranbah North Sample Simtars Testing	Air	1	21.06	78.00	N.D.	N.D.	0.0356	N.D.	N.D.	-0.16	-	-	-	-
	47.8	1	20.74	78.15	0.1003	8	0.0972	N.D.	31	0.20	0.40	0.01	1.0	0.3
	63.5	2	20.57	78.42	0.0192	24	0.0854	N.D.	15	0.44	0.54	0.05	3.0	1.0
	87.2	3	20.43	78.58	0.0031	82	0.0739	Trace	8	0.63	1.30	0.21	10.3	3.4
	108.9	7	19.92	79.03	0.0015	225	0.1113	Trace	5	1.26	1.79	0.30	28.1	9.4
	128.4	18	18.88	79.94	0.0014	556	0.2028	1	5	2.54	2.18	0.33	69.5	23.2
	150.8	42	16.92	81.60	0.0022	1308	0.395	2	9	4.95	2.64	0.36	163.5	54.5
	176.4	131	9.29	87.95	0 008	4837	1.2346	14	34	14 28	3.39	0.40	604.6	201.5
	212.8	124	0.79	92.26	0.0311	17474	4.0671	109	103	23 93	7.30	0.43	2184.3	728.1

N.D. – not detected   Trace - <1ppm

Problems are apparent when comparing small scale testing and large scale testing with regards to the carbon monoxide to carbon dioxide ratio. There appears to be favoured production of carbon monoxide from incomplete combustion because of the lack of oxygen. This is evident in the figure published by F. Clarkson (Simtars) in 2006 where the small scale generated ratio continues to climb with temperature whereas the large scale doesn't show much increase over 75°C (Figure 22). Figure 17 reflects this as well with the small scale results continuing to increase with temperature. The lack of any real increase in the $CO:CO_2$ ratio for the Grosvenor sample up to approximately 80°C is further evidence for doubts over the suitability of the carbon monoxide to carbon dioxide ratio for early detection of spontaneous combustion.

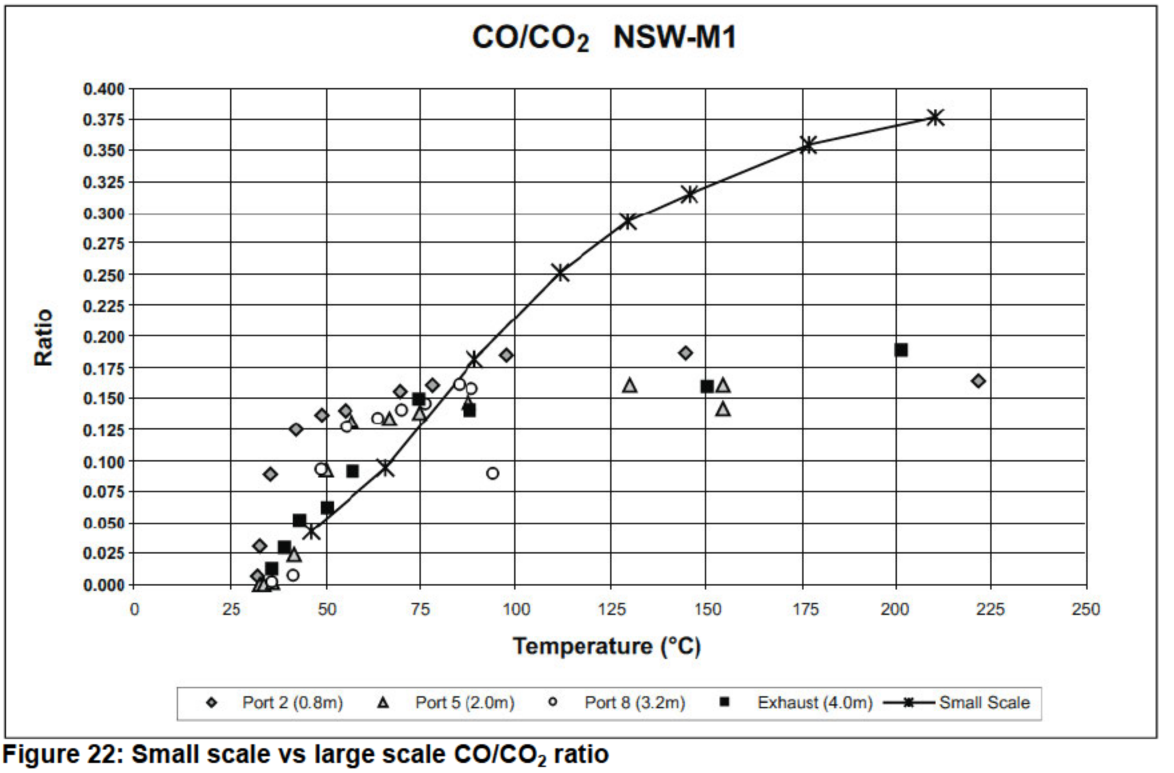

Figure 22: Small scale vs large scale CO/CO_2 ratio

Gas evolution data results of absolute concentrations of gases determined at various coal temperatures cannot be directly transferred to TARP levels. The ratios of gases and appearance temperatures are more important.

It must be noted that although used to assess the propensity or likelihood of coal to spontaneously combust, tests such as R70 do not provide information that can be used for setting trigger levels.

Points of note from testing:

- Earliest ethylene appearance >1ppm 100°C.
- Graham's ratio (a known measure of intensity) is approximately 1.5 at 100°C.
- Carbon monoxide concentration at 60°C almost 2.5 times that at 45°C and increased by a factor of at least 10 between 45 and 100°C.
- The lowest ratio of ethylene to carbon monoxide when ethylene at least 1ppm was 1:150 with Graham's ratio at least 1.

3.2 Triggers for Spontaneous Combustion in Active Goaf

With a new technique in mining come new possibilities for sample locations. The three typical sample locations used in active goaf (longwall) TARPs elsewhere include longwall return, goaf stream and active goaf seals. Previous experience has shown that if conditions for each of these locations are given, TARPs become clearer to read and understand and there is no confusion over which conditions apply to which location.

Table 3 outlines the gas parameters recommended for setting triggers for each of the sample locations.

Table 3: Recommended gas parameters and sample locations

Sample Location	**Parameter**
Longwall Return	CO Make Graham's Ratio $CO:CO_2$ Ratio (Normal and Level 1 only) Ethylene
Goaf Stream	Raw Carbon Monoxide Graham's Ratio Ethylene
Active Seals	Raw Carbon Monoxide Graham's Ratio Ethylene

MDG1006 and the Moura No. 2 Warden's Inquiry both make mention of the importance of physical indicators in the detection of spontaneous combustion. There have been multiple events in which physical indicators were observed but dismissed or reports "lost" in the system. The importance placed on them would support having them as a Level 2 trigger, with the exception of smoke from the goaf which would be more appropriately used as a Level 3 Trigger. As a trigger for Level 2 the investigation into these indicators would be required. It is important that reports of physical signs be investigated and not dismissed.

It is recommended that gas chromatograph results not be used to trigger CO Make or Graham's Ratio Triggers in Longwall returns, the tube bundle system is best suited for picking up spontaneous combustion from this sampling location. Although not as reliable as tube bundle (but specifically referred to in legislation) real time is also better than the gas chromatograph for monitoring this location.

It is outside the scope of this review to make an informed or quantitative comment on the inclusion of a trigger for slower longwall production although inclusion as a Level 1 Trigger is recommended. Longwall mining has not been practised at Grosvenor as yet and new mining techniques and equipment elsewhere has often been associated with teething problems and delays. During normal operations there is generally an area in the goaf that is being supplied enough air for oxidation but at an insufficient velocity to take away any heat that is generated. As the longwall retreats this area is continually changing and therefore temperature increase limited. When longwall mining is slowed (for a significant period of time not just a day or two) there is a greater chance for the temperature to increase. Inclusion at Level 1 would trigger increased monitoring and awareness allowing early detection possible. Increased monitoring at active seals inbye the face is recommended along with at least daily goaf stream sampling. An answer best dealt with by site is how much slower and over what time period before being triggered. Of course if Grosvenor established and implements a comprehensive monitoring regime including tube bundle monitoring points inbye the longwall, such a trigger would not be required. The intent of this trigger is to increase sampling during a period where increased oxidation is likely so as to identify any increased intensity. If such monitoring already exists it is not required. The monitoring envisaged would be a combination of tube bundle monitoring and bag sampling of inbye the longwall, through maingate seals, where oxygen concentrations remains above 12%.

3.2.1 Normal Background

Establishing what constituents a normal value is important in determining when an abnormal state has been reached. This allows actions to be taken to confirm situation and to start implementing controls. A balance is required in setting the triggers so that alerted to an abnormal situation but not too sensitive so as to be generating what are perceived as nuisance alarms.

As discussed, based on proximity, coal being mined and availability of results, data from Moranbah North has been used to establish expected background values. The data used is the same as that used by the author for recommending Trigger Levels for Moranbah North.

It is normal for no ethylene to be found at any sample location in the absence of any elevated oxidation activity. No additional comment has been made relating to this for individual sample locations.

Values recommended to be used as Normal Thresholds are summarised in

Table **4**. Detailed discussion for each parameter can be found below.

Table 4: Recommended Normal Thresholds

Level	Normal
Longwall Return	CO Make less than 30l/min AND Graham's Ratio less than 0.3 AND CO/CO_2 less than 0.2 AND No Ethylene
Goaf Stream Bag Sample	Raw Carbon Monoxide less than 100ppm AND Graham's Ratio less than 0.3 AND No Ethylene
Active Goaf Seal	Raw Carbon Monoxide less than 100ppm AND Graham's Ratio less than 0.3 AND No Ethylene

Longwall Return

CO Make

The CO Make for tube bundle data provided for LW108, LW109 and LW601 is shown in Figure 23. The CO Make was regularly in excess of the upper normal limit set at the time, indicating that either abnormal oxidation was commonly occurring or the upper normal threshold was set to low. It was more likely that the threshold was set too low as indicated by the lack of a definitive upward trend and low and relatively stable absolute carbon monoxide concentrations and Graham's ratio as seen in Figure 24, Figure 25 and Figure 26. There is also a notable difference in the magnitude of the data from LW601 compared to LW108 and LW109. As can be seen the CO make is generally less than 30l/min for the 100 side panels and less than 40l/min for LW601.

The CO Make for LW109 did exceed 30l/min for a significant period in late 2012 but this was at a time that elevated CO was being seen at 39c/t and increased oxidation suspected. Figure 27 shows how the CO Make and active goaf seal data both highlight a time of abnormal oxidation in LW109 (in the vicinity of 39c/t). As such this period has been discounted as "normal". LW601 also returned CO Make values greater than 40l/min particularly towards the end of the data, but this is at a time where some elevated levels of carbon monoxide are seen elsewhere and again discounted as normal. The raw carbon monoxide concentrations in the longwall return are shown in Figure 28.

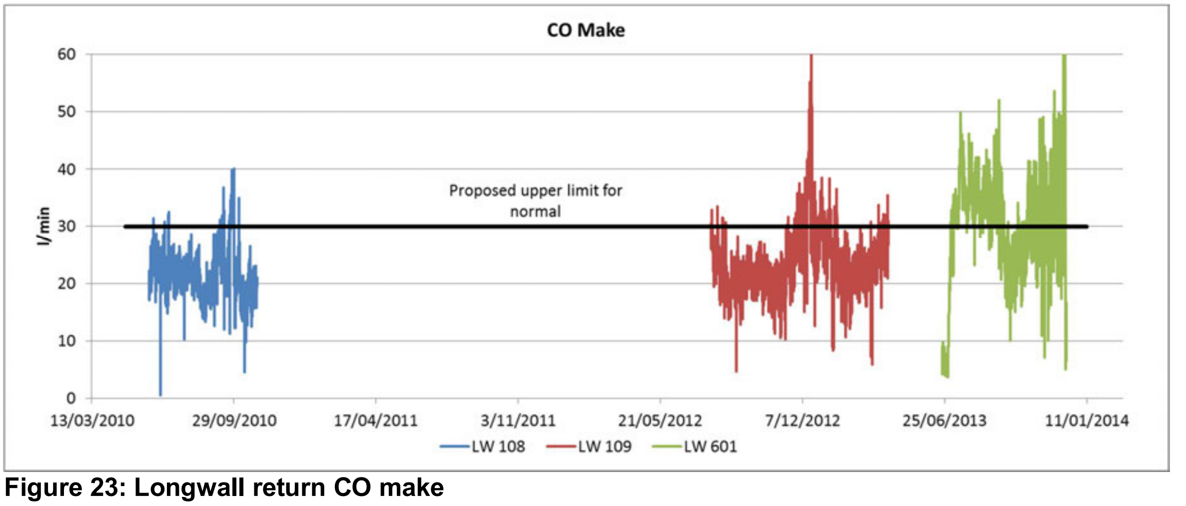

Figure 23: Longwall return CO make

It is recommended that a conservative approach be applied when using Moranbah North data for setting normal values for Grosvenor and that the lower value of 30l/min from the 100 side panels be used. MSIA has been advised that the longwall face design quantity is 75m^3/s. A CO Make (independent of quantity) of 30l/min would equate to a raw carbon monoxide concentration of 6.7ppm at that ventilation quantity.

Figure 30 shows the oxygen deficiency in longwall returns for Moranbah North. Typically ventilation quantity was less than that planned for Grosvenor and as such Grosvenor could expect less oxygen deficiency. Assuming that the oxygen deficiency was of the order of 0.3 to 0.4, 6.7ppm of carbon monoxide would return a Grahamǒs ratio of between 0.17 and 0.22. This is in line with normal oxidation.

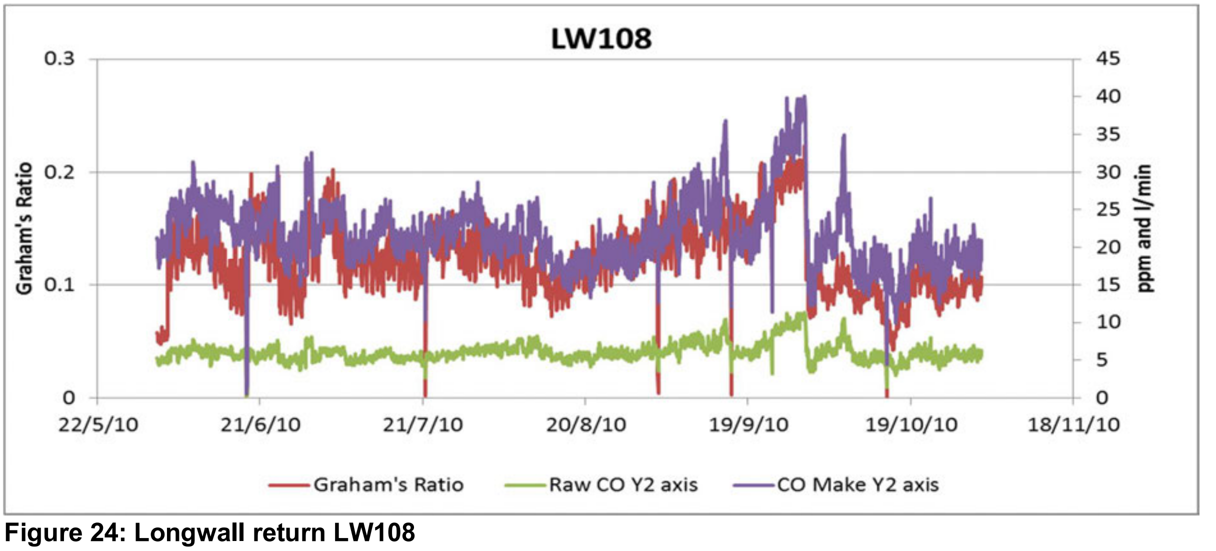

Figure 24: Longwall return LW108

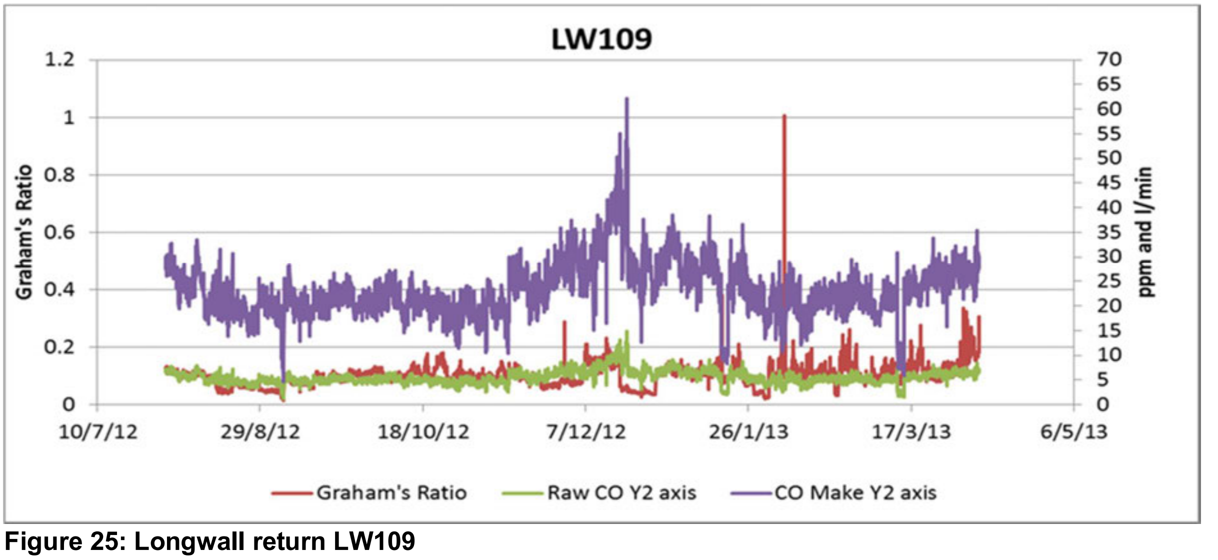

Figure 25: Longwall return LW109

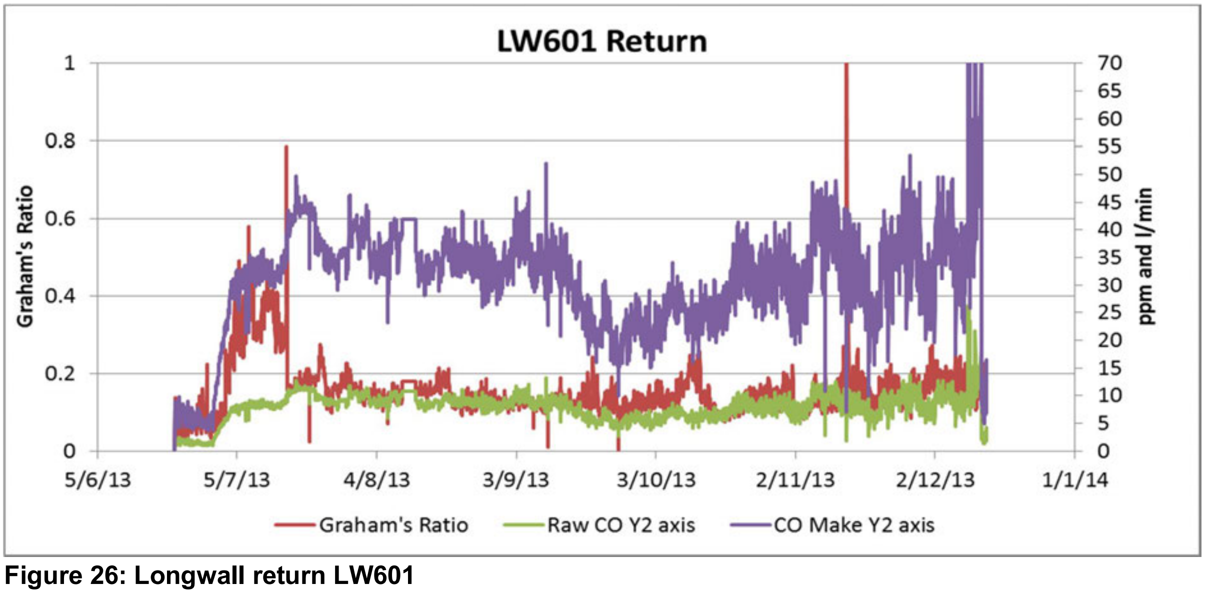

Figure 26: Longwall return LW601

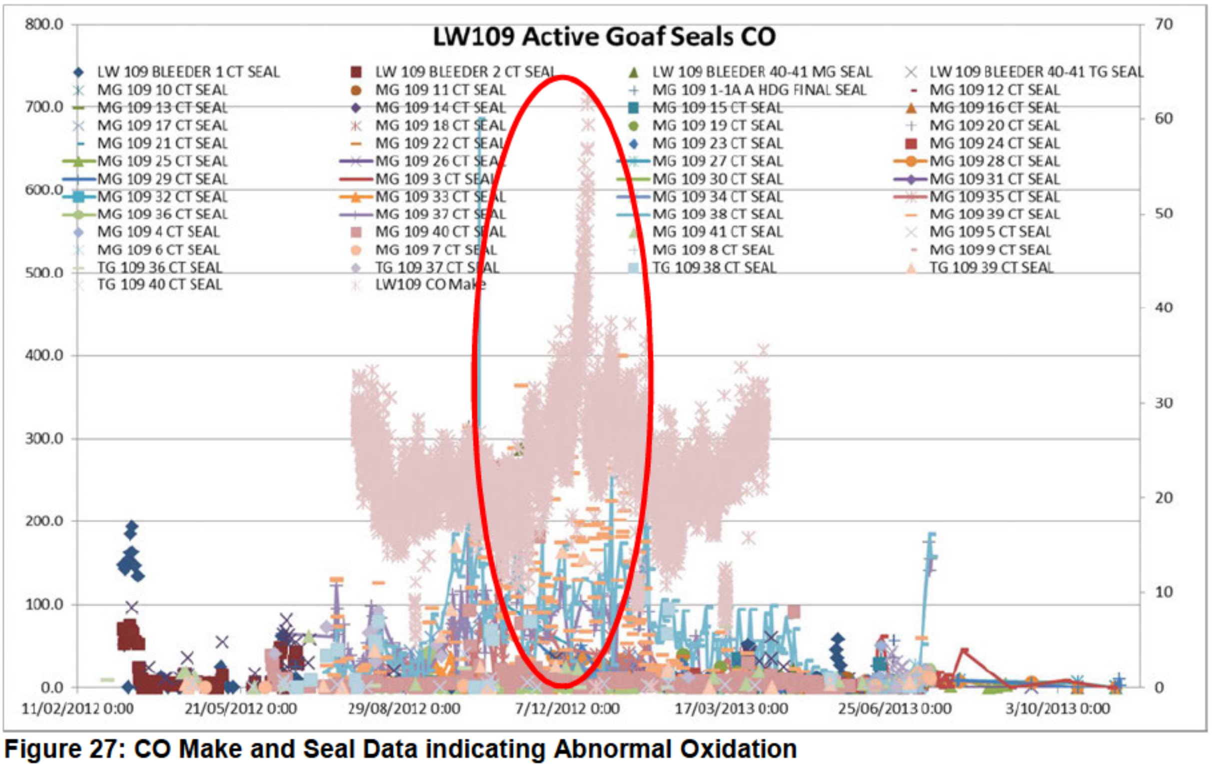

Figure 27: CO Make and Seal Data indicating Abnormal Oxidation

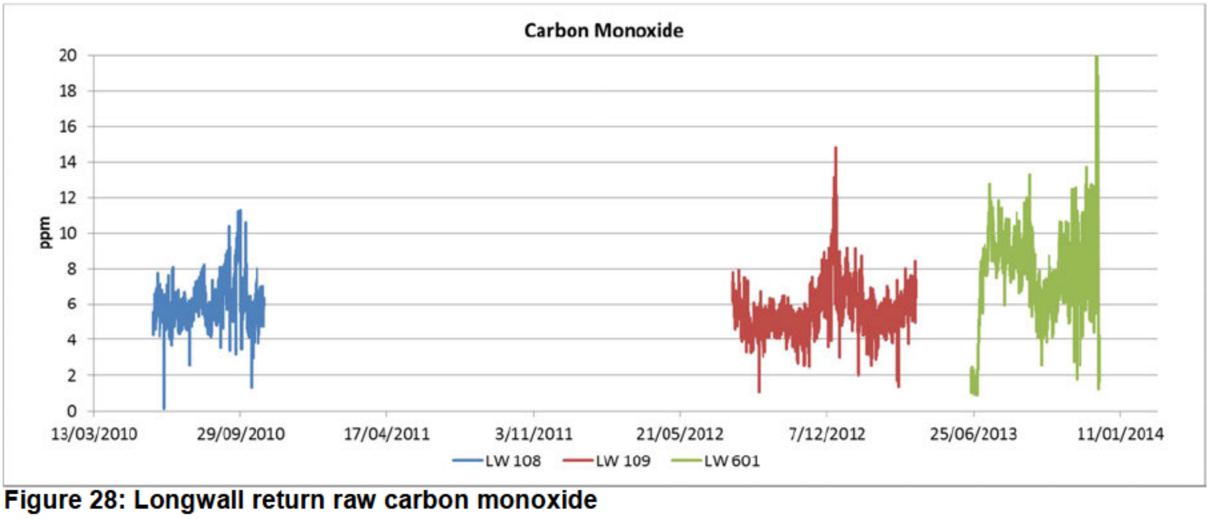

Figure 28: Longwall return raw carbon monoxide

Graham's Ratio

Figure 29 shows a plot of Graham's ratio in the longwall return for LW108, LW109 and LW601. As can be seen the majority of samples returned values less than 0.2 and nearly all of the values were less than 0.3. Figure 30 shows the oxygen deficiency for the same locations over the same period and a comparison shows (particularly for LW601) that often when the Graham's ratio was elevated it coincided with oxygen deficiency values less than 0.2. An oxygen deficiency of at least 0.2 is required for Graham's ratio to be considered reliable.

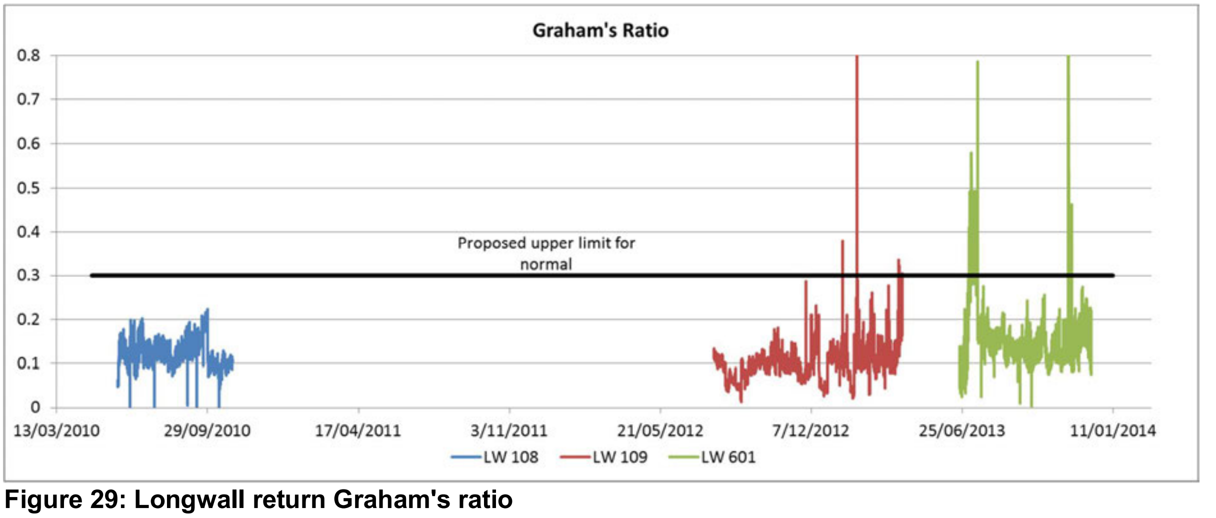

Figure 29: Longwall return Graham's ratio

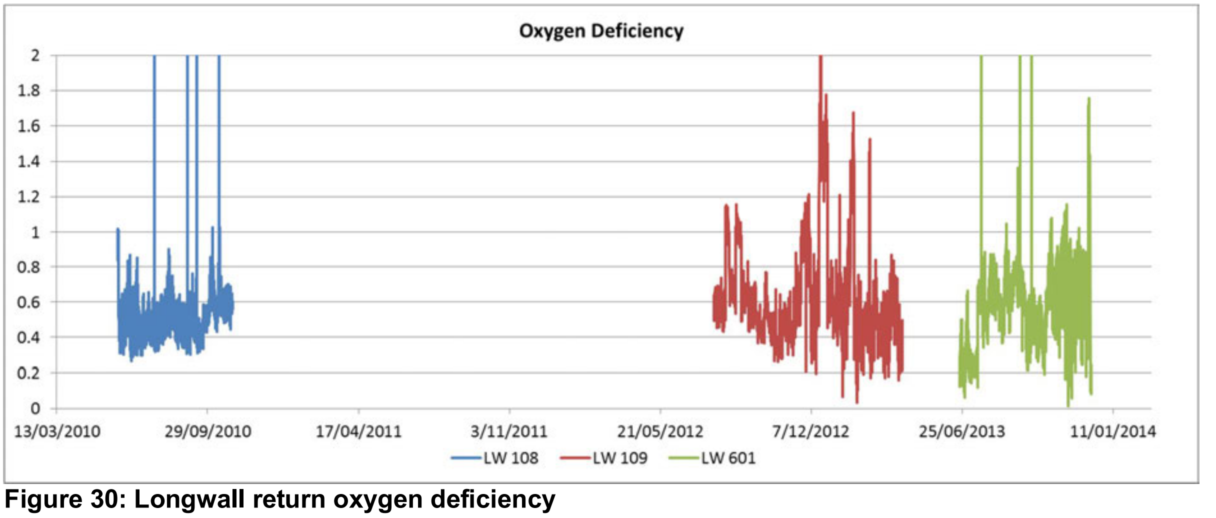

Figure 30: Longwall return oxygen deficiency

Oxygen deficiency is a measure of how much oxygen is used in oxidation reactions. An efficient (i.e. HOT) reaction is efficient in converting oxygen into oxidation products when it reacts with coal. Warmer coal uses less oxygen to produce the same amount of carbon monoxide. Although not a trigger the normal oxygen deficiency in the longwall return is a useful tool when setting triggers for higher levels. Figure 30 shows the typical oxygen deficiency in the longwall return as measured by tube bundle. The average oxygen deficiency is approximately 0.56 but a value of 0.5 has been used in in subsequent calculations in order to maintain a conservative approach in setting triggers.

Gas evolution testing returned a Graham's ratio of 0.67 for the Grosvenor sample and 0.40 for the Moranbah North sample at temperatures of 42°C and 48°C respectively. The Moranbah North sample returned a Graham's ratio of 0.54 at 63.5°C. It has been noted elsewhere that CB3 testing has returned higher Graham's ratio values than Simtars testing at lower temperatures. A value of less than 0.4 is regularly quoted as being "Normal" in literature. Based on this and the results observed at Moranbah North a value of 0.3 is recommended as the upper normal level for the longwall return.

Carbon Monoxide:Carbon Dioxide Ratio

The carbon monoxide:carbon dioxide ratio for Moranbah North longwall return tube bundle data provided is shown in Figure 31. As can be seen the majority of samples return values of less than 0.2, although LW601 tended to return higher values. Figure 32 shows that the spikes seen for the $CO:CO_2$ are mainly due to low carbon dioxide concentrations approaching that of ambient air. The ambient concentration (0.035%) is subtracted from the measured amount in an effort to include only the carbon dioxide produced by oxidation. The values for this ratio seen for the Moranbah North data collected from the tube bundle is much higher than that considered normal. Gas evolution testing of the Moranbah North coal sample returned a value of 0.01 for ~40°C and the Grosvenor sample returned a value of 0.03 for a similar temperature. The reference Spontaneous Combustion in Australian Coal Mines (2015) refers to 0.02 as being typical of normal coal temperatures.

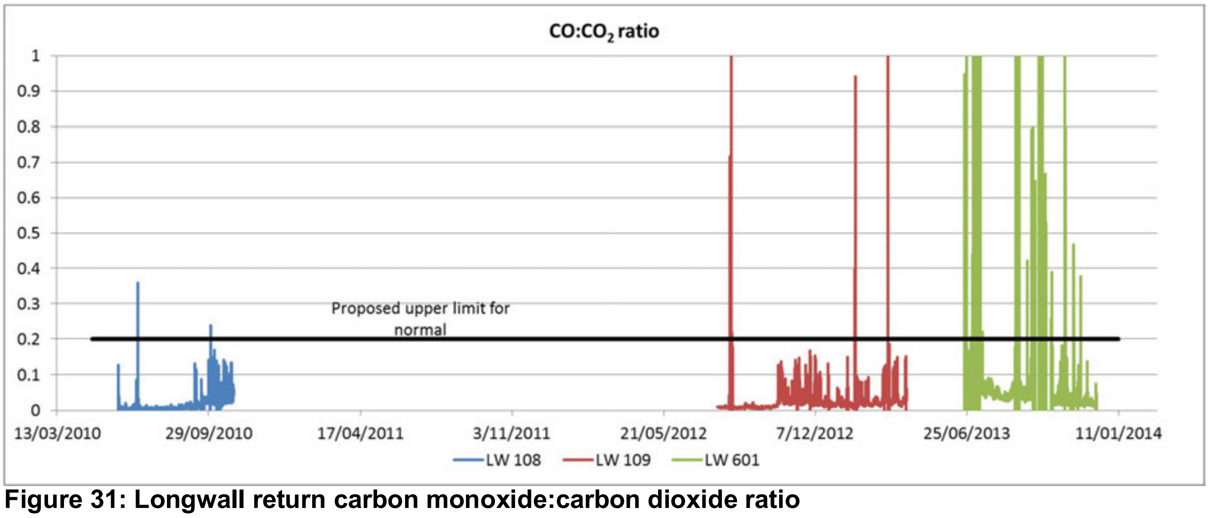

Figure 31: Longwall return carbon monoxide:carbon dioxide ratio

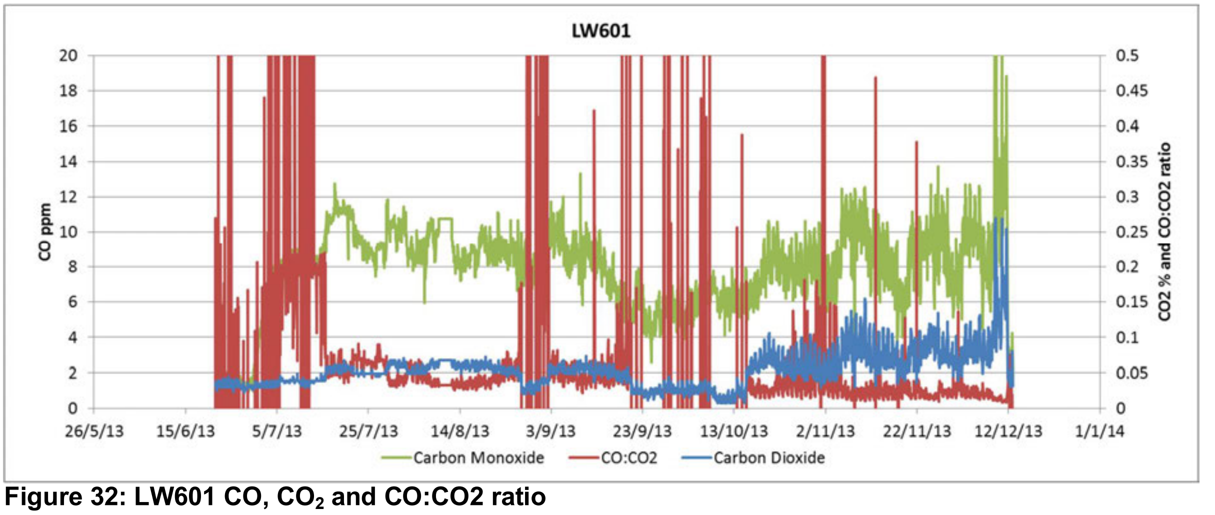

Figure 32: LW601 CO, CO_2 and CO:CO2 ratio

Legislation calls for alarming on the CO/CO_2 ratio. Although noted as being high, until Grosvenor can establish their own background carbon monoxide:carbon dioxide ratios it is recommended that the value of 0.2 be used as the upper threshold limit for normal. As already discussed there are some issues with this ratio and it is not recommended that it be used for triggering any response above Level 1. The use of other spontaneous combustion indicators means that safety or asset protection is not compromised by use of a higher trigger level.

Goaf Stream

Carbon Monoxide

All data for the goaf stream comes from analysis of bag samples collected and analysed by gas chromatography. The raw carbon monoxide concentrations for samples collected from the goaf stream of four goaves are shown in Figure 33. As was observed for CO Make there appears to be a difference in the concentration between the different sides of the mine, with the 100 side (LW108 and LW109) returning lower concentrations than LW203 and LW601. The majority of LW108 and LW109 samples were less than 100ppm. LW203 and LW601 returned more results over 100ppm but the majority were less than 120ppm.

As was applied for Longwall return CO Make a conservative approach is recommended to the setting of the upper normal limit for carbon monoxide in the goaf stream with a bias to the data from the 100 side. As such an upper limit of 100ppm is recommended.

Graham’s Ratio

As can be seen in

Figure 34, Graham�above ratio was generally less than 0.3 for all goaf stream samples although there were spikes greater than this. These spikes were often associated with low oxygen deficiency rather than elevated carbon monoxide. Oxygen deficiency for the four locations is shown in Figure 35.

In line with that recommended for the longwall return, gas evolution testing and theoretical values an upper limit of 0.3 is recommended for Graham‰s ratio in the goaf stream.

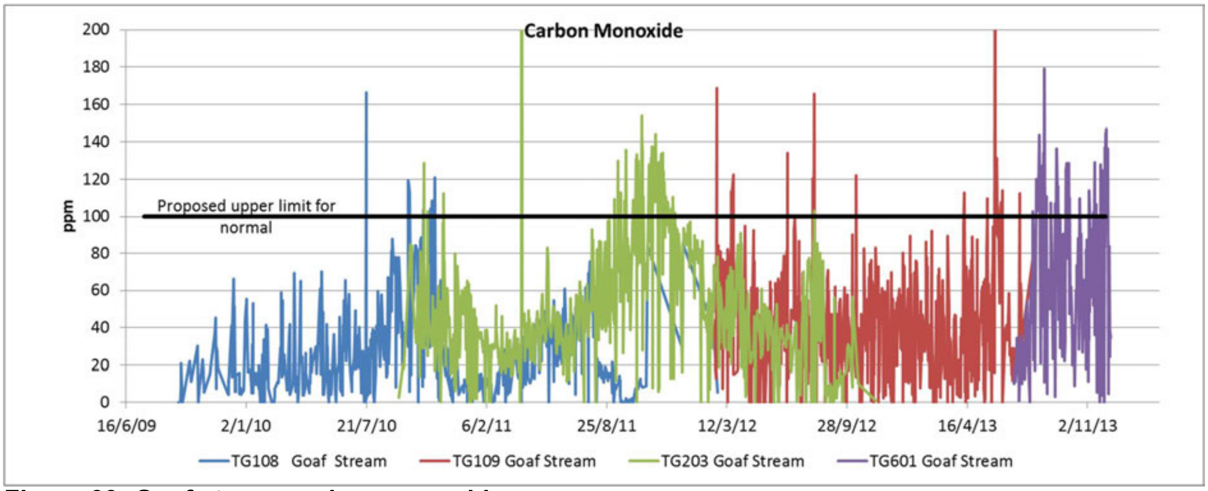

Figure 33: Goaf stream carbon monoxide

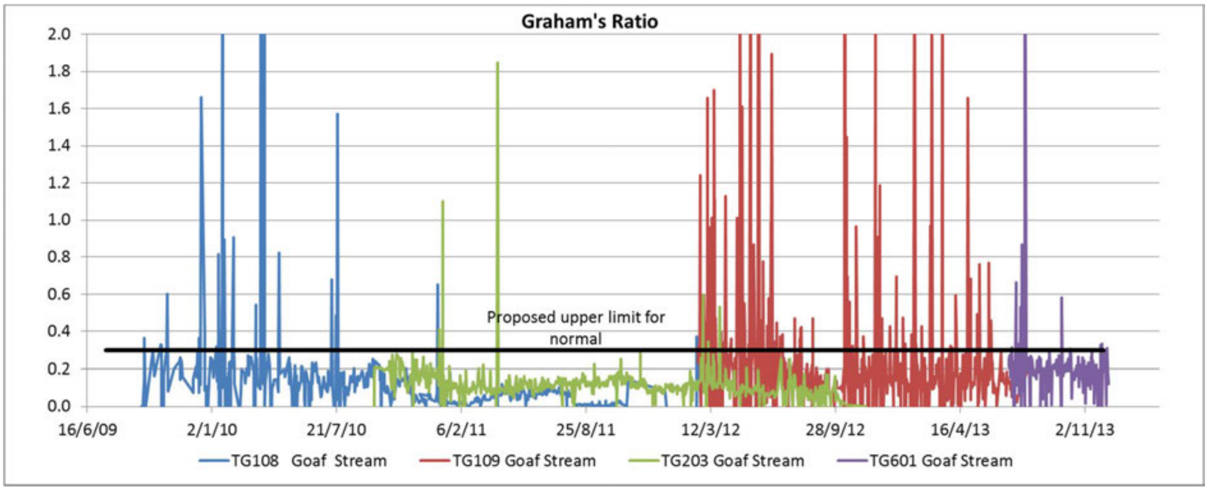

Figure 34: Goaf stream Graham's ratio

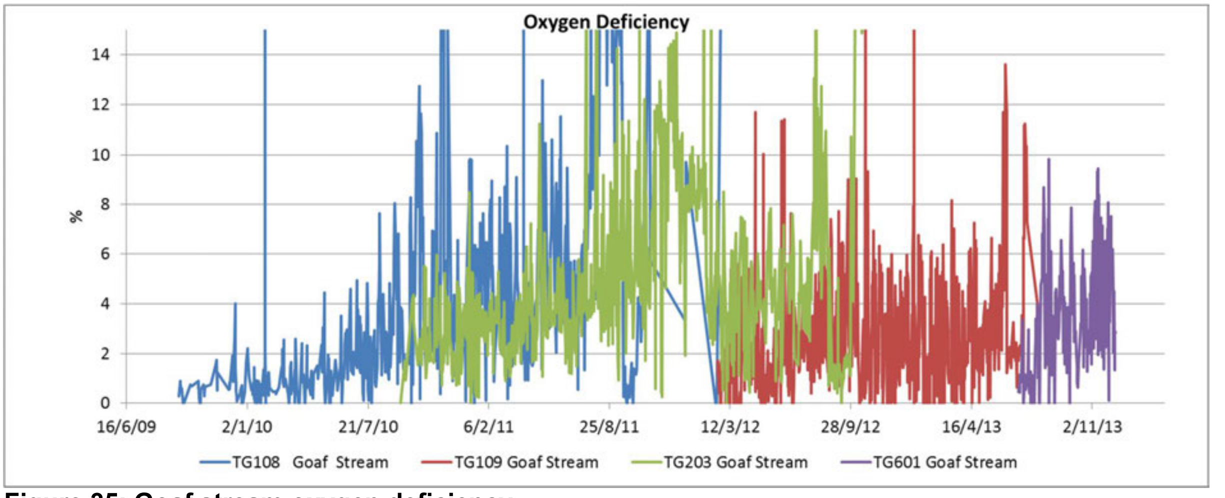

Figure 35: Goaf stream oxygen deficiency

Active Goaf Seals

Carbon Monoxide

Generally in the absence of any abnormal oxidation, carbon monoxide is less than 100ppm for active seals, as seen in Figure 36 and Figure 37. Figure 38 shows the GC data for LW108 for which the majority of data is less than 100ppm. The exception is the carbon monoxide measured at 1 c/t in the bleeder. It is possible that some elevated oxidation was occurring as oxygen was elevated for prolonged times in this area and was a situation worthy of further investigation.

Figure 39 shows that the carbon monoxide for LW109 seals was also normally less than 100ppm with the exception of 39c/t and 38c/t during a time known to have been experiencing elevated oxidation. Figure 40 shows the carbon monoxide concentration in LW203 was generally less than 100ppm. The data for LW601, displayed in Figure 41, shows more variation in results from different locations. Although some locations are regularly above 100ppm, many are below. This does not appear to be typical behaviour and as such warrants investigation.

The upper limit for normal for active goaf seals is recommended to be set at 100ppm.

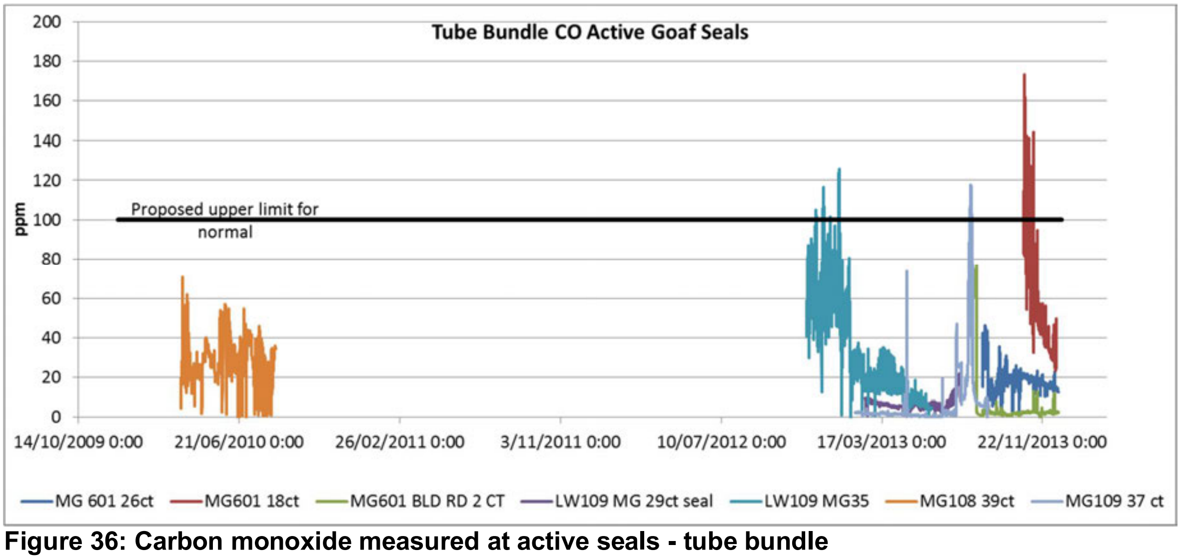

Figure 36: Carbon monoxide measured at active seals - tube bundle

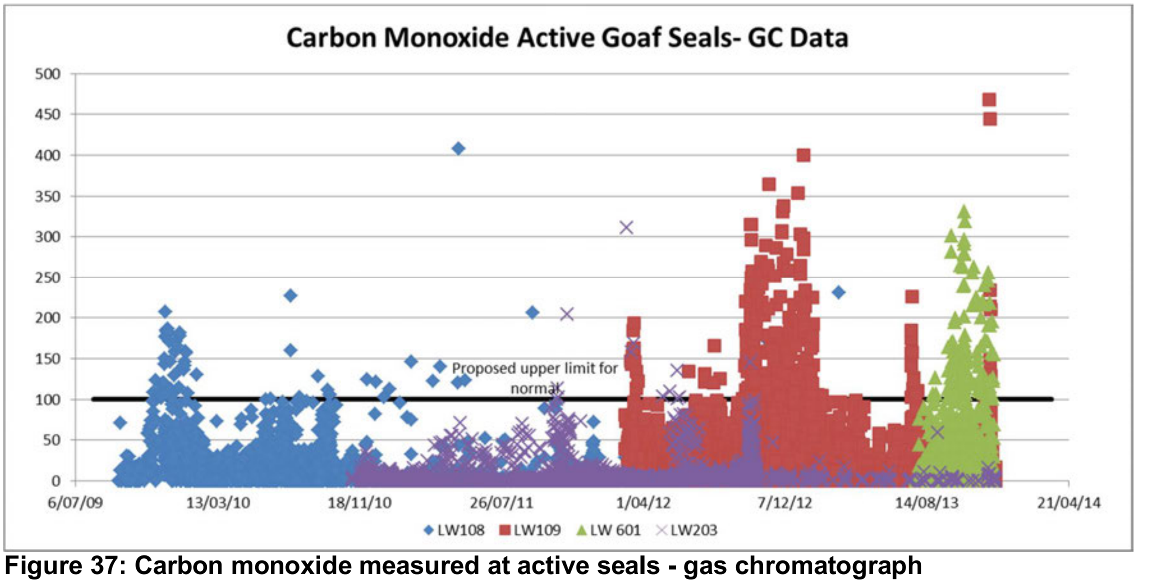

Figure 37: Carbon monoxide measured at active seals - gas chromatograph

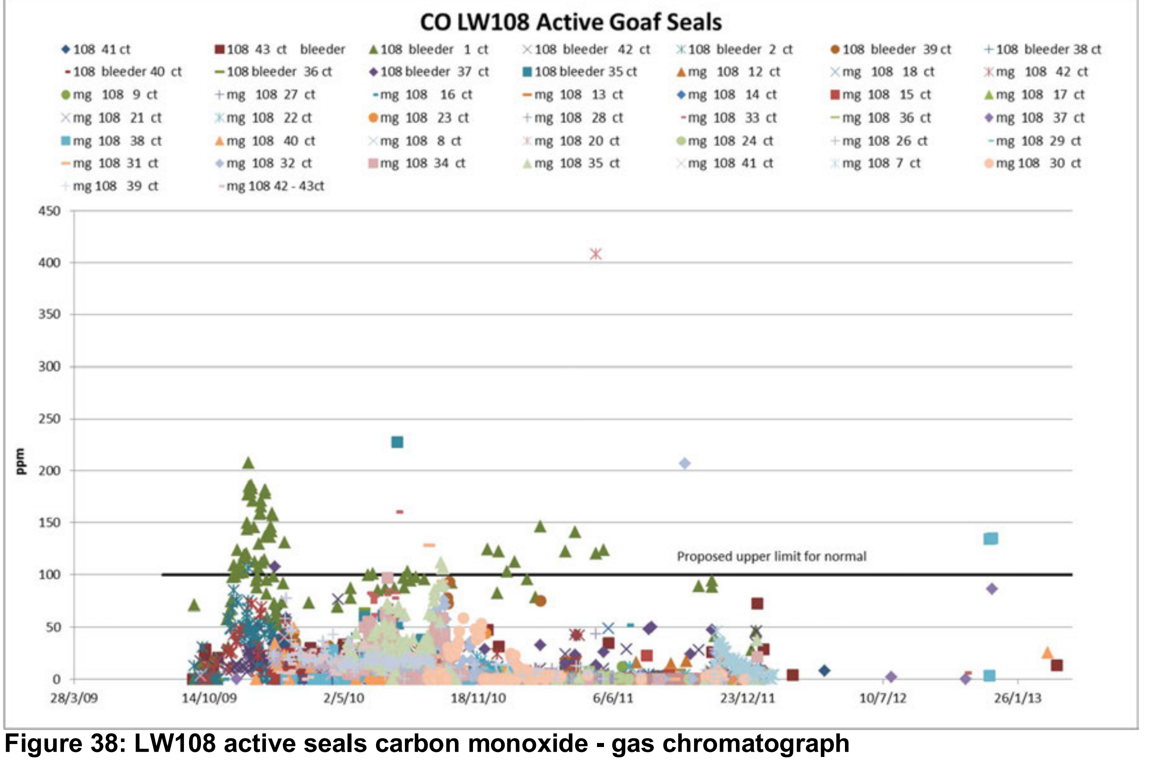

Figure 38: LW108 active seals carbon monoxide - gas chromatograph

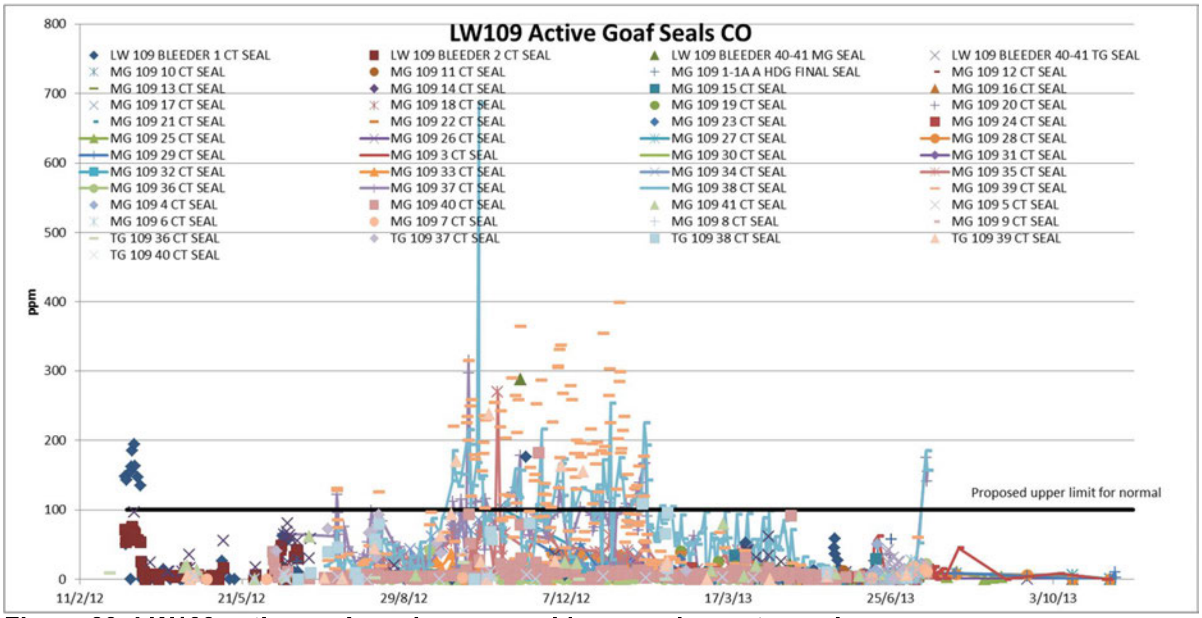

Figure 39: LW109 active seals carbon monoxide - gas chromatograph

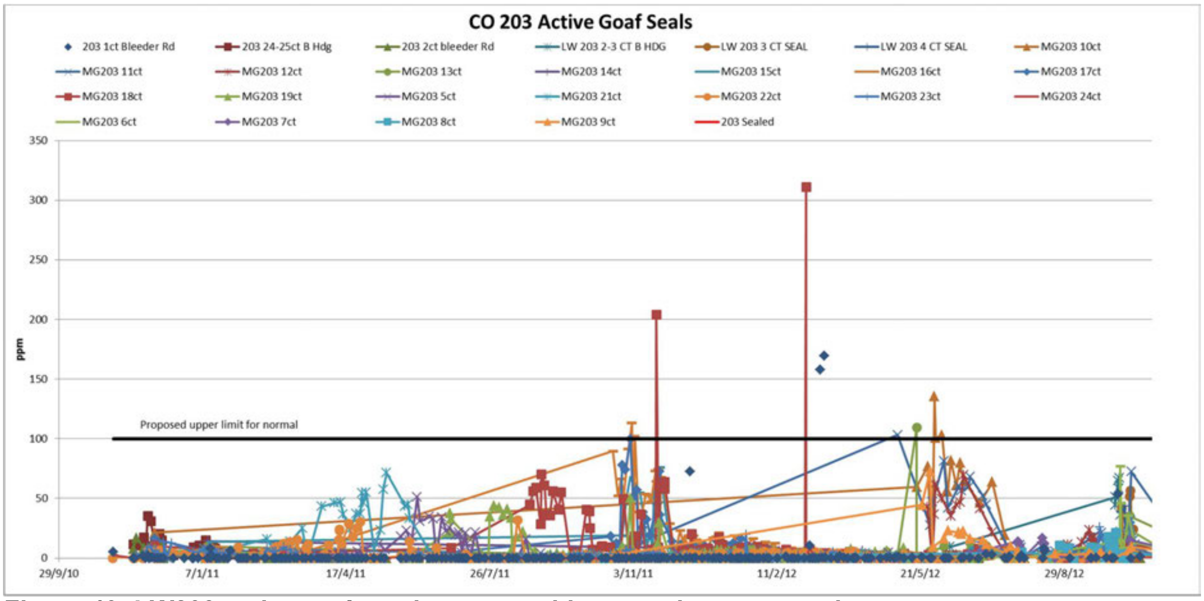

Figure 40: LW203 active seals carbon monoxide - gas chromatograph

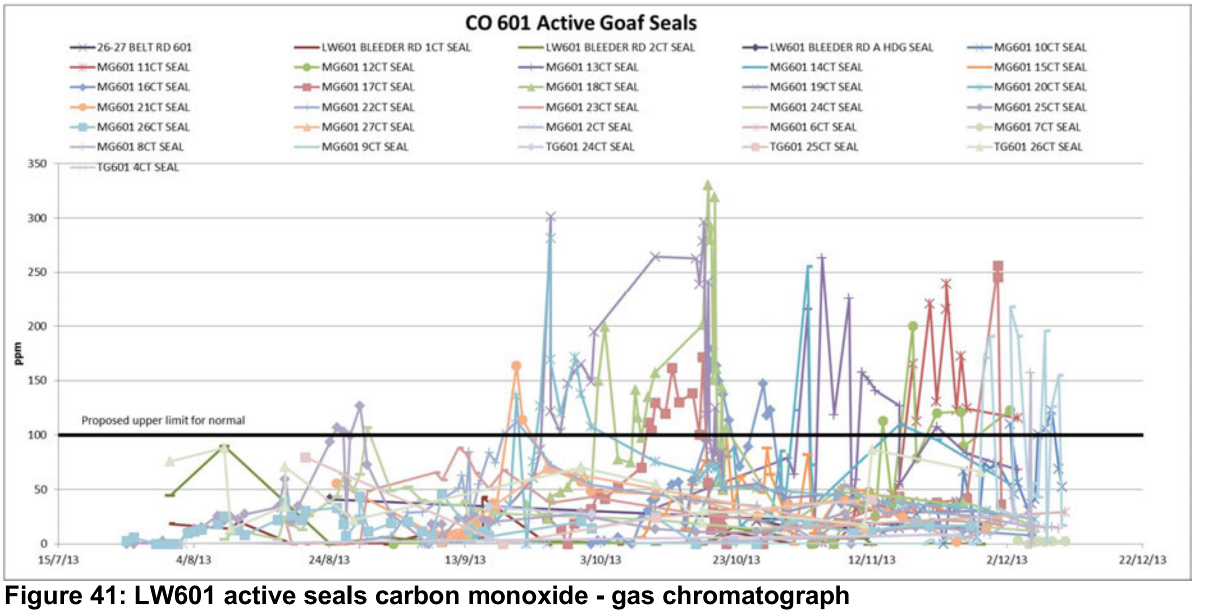

Figure 41: LW601 active seals carbon monoxide - gas chromatograph

Graham's Ratio

Graham's ratio is generally accepted as only being representative if there is an oxygen deficiency greater than or equal to at least 0.2. The calculated Graham's ratio tends to be exaggerated if the oxygen deficiency is less. Figure 42 and Figure 43 show the calculated Graham's ratio for tube bundle and gas chromatography analysis respectively. During times of no known elevated oxidation activity the value tends to be less than 0.3. Many of the higher spikes are as a result of low oxygen deficiencies, rather than elevated oxidation.

Individual plots of Graham's ratio calculated from Gas chromatograph results for each of the longwall blocks reviewed are shown in Figure 44 - Figure 47.

Based on background data from Moranbah North, gas evolution testing, theoretical values and values recommended for other sampling locations, an upper limit for Graham's ratio at active goaf seals of 0.3 is recommended.

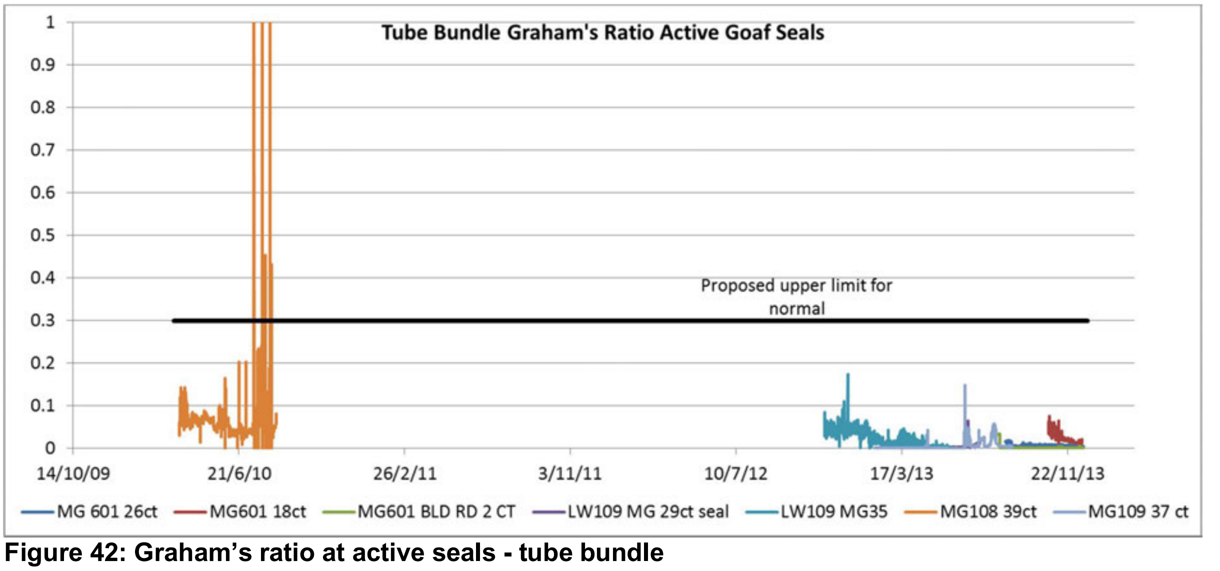

Figure 42: Graham's ratio at active seals - tube bundle

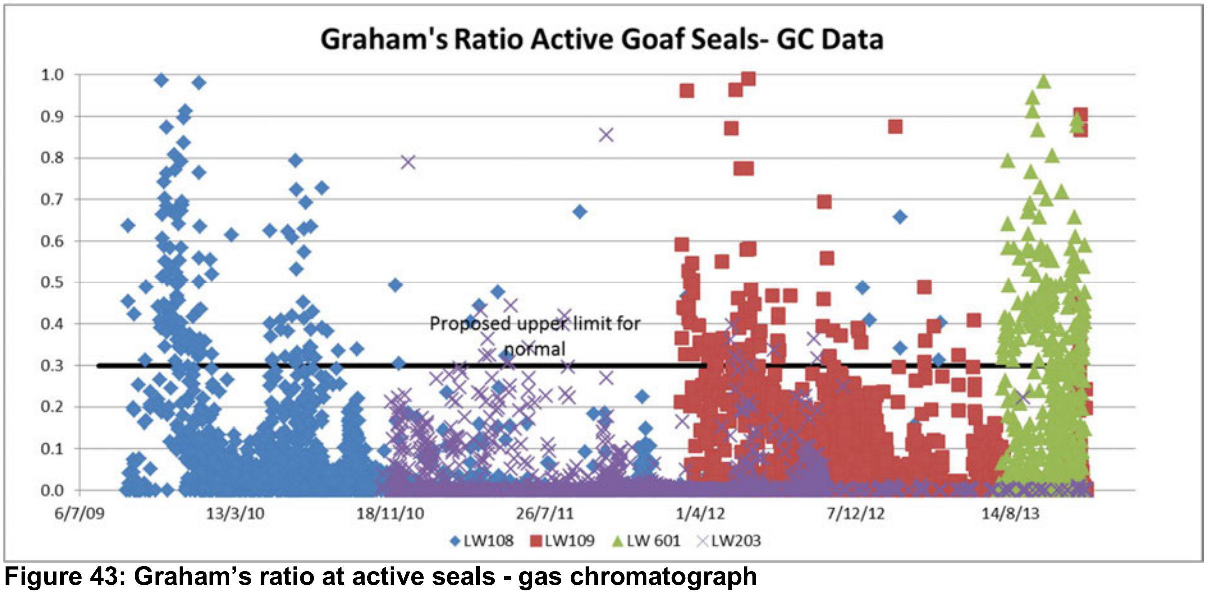

Figure 43: Graham's ratio at active seals - gas chromatograph

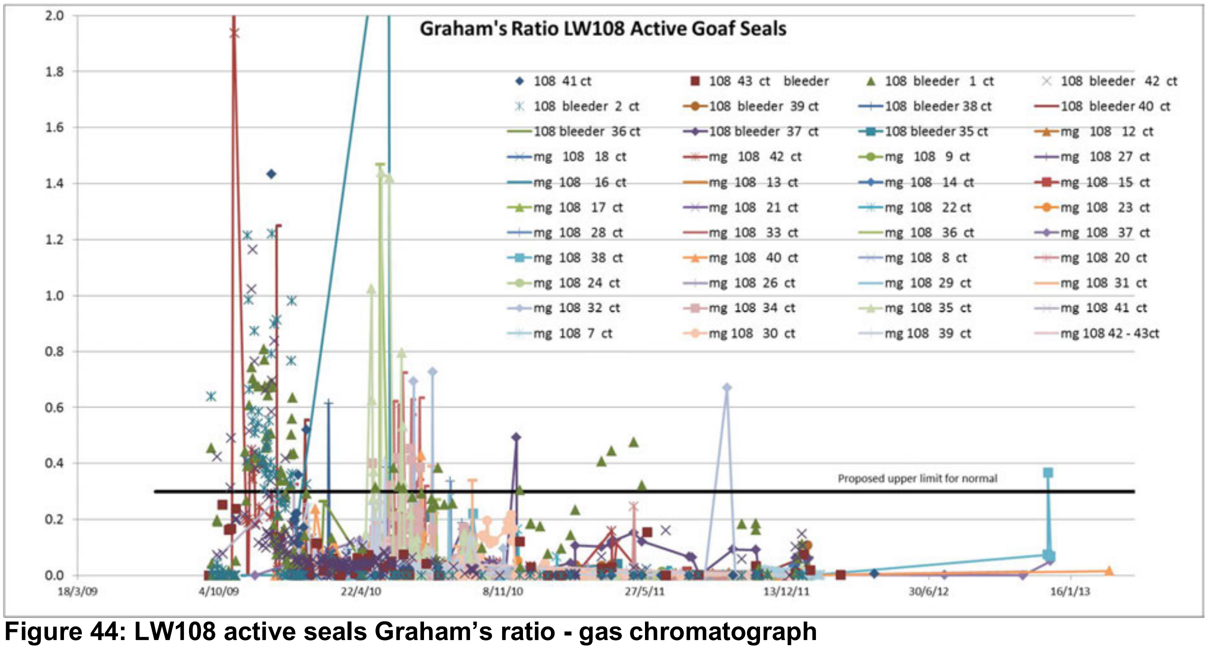

Figure 44: LW108 active seals Graham's ratio - gas chromatograph

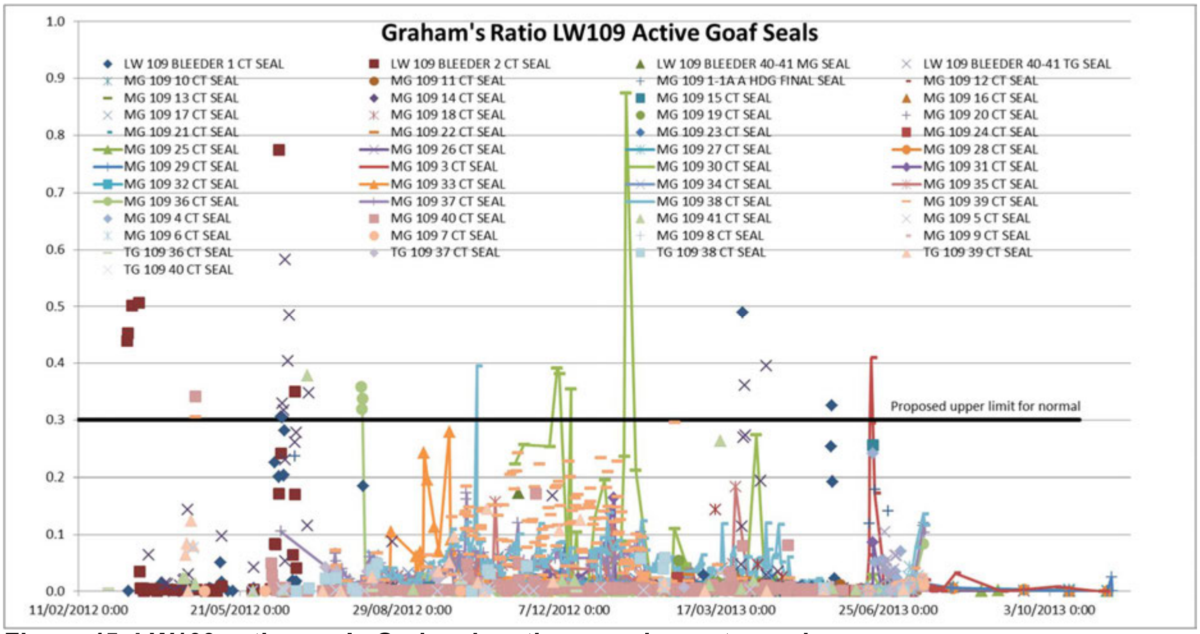

Figure 45: LW109 active seals Graham's ratio - gas chromatograph

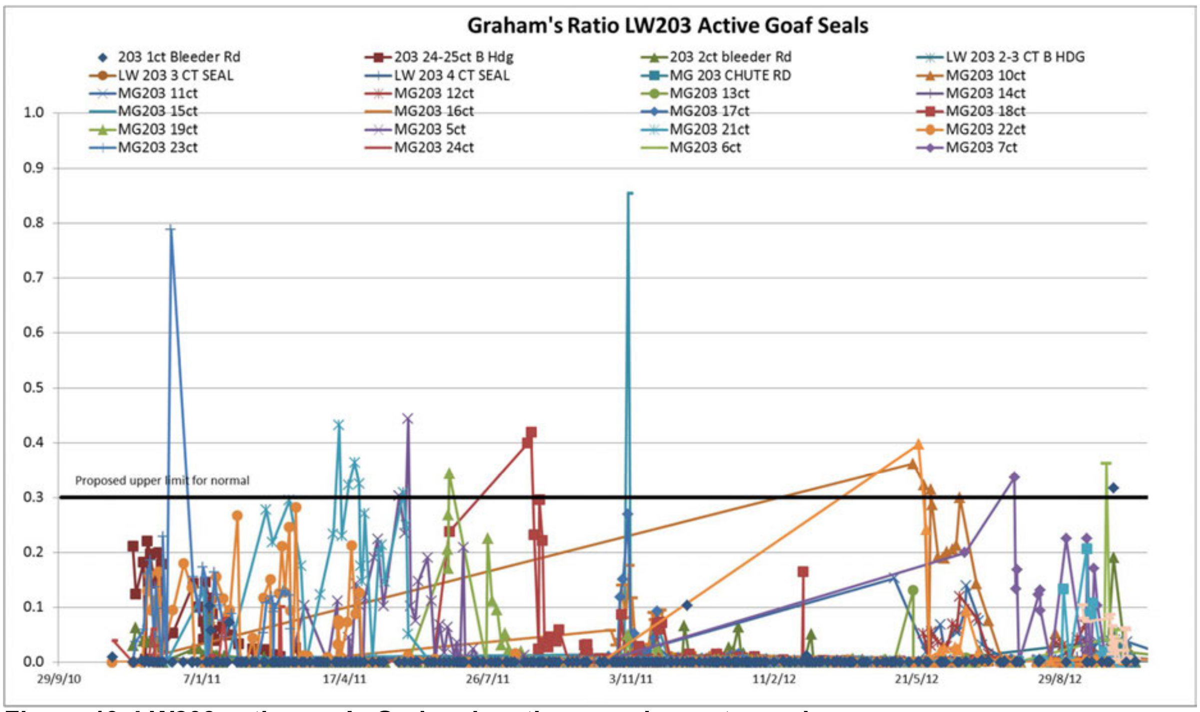

Figure 46: LW203 active seals Graham's ratio - gas chromatograph

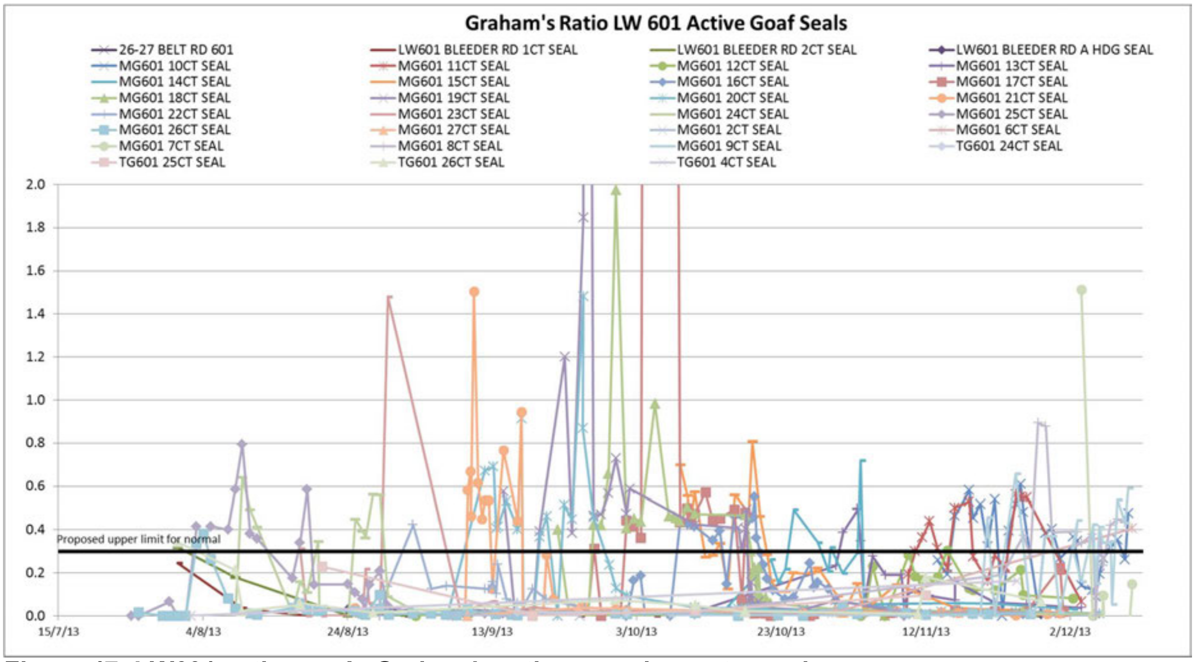

Figure 47: LW601 active seals Graham's ratio - gas chromatograph

3.2.2 Level 1

Level 1 triggers indicate that the results are no longer normal and warrant investigation, often resulting in additional sampling. The initial aim is to establish whether or not a spontaneous combustion event has initiated but should not preclude the implementation of controls to stop any increase in intensity if investigation confirms elevated oxidation is occurring. The approach with the setting of the Level 1 Triggers is to have a narrow range of results that are above normal and instigate investigation and confirmation of early stages of any oxidation activity. Linked with the setting of normal parameters the earlier this is established the more time and better chance of successfully controlling the situation. By default the upper limits of Level 1 become the lower limits for Level 2 Triggers, typically where more significant efforts are put into controls. Results in this trigger level should not present an unacceptable level of risk. The trigger level to initiate a Level 1 Response is greater than what is normal which has already been discussed. Where possible the setting of the upper limit for this Level is recommended at matching indicators with test data at approximately 60°C.

Laboratory testing returned a Graham's ratio of 0.82 at 60°C for the Grosvenor sample tested at CB3. The Moranbah North sample tested at Simtars returned a Graham's ratio of 0.54 at 64°C. The carbon monoxide concentration increased by a factor of 2.7 from 42°C to 60°C for the Grosvenor sample. There was a threefold increase in carbon monoxide between 48°C and 64°C for the Moranbah North sample. It must be noted that the factor of increase observed in small scale testing is as a result of all of the coal involved in producing carbon monoxide increasing to the same temperature. This is unlikely in any underground oxidation, particularly in the early stages. As such a more conservative approach is required. No ethylene should be detected in this target temperature range and as such ethylene is not mentioned in triggers for this level.

Recommendations are summarised in Table 5.

Table 5: Recommended Level 1 Triggers

Level	Level 1 Response
Longwall Return	**30l/min ≤ CO Make < 50l/min** **OR** **0.3 ≤ Graham's Ratio <0.5** **OR** **CO/CO_2 ≥ 0.2**
Goaf Stream	**100ppm ≤ Raw Carbon Monoxide < 200ppm** **OR** **0.3 ≤ Graham's Ratio <0.5**
Active Goaf Seal	**100ppm ≤ Raw Carbon Monoxide < 200ppm** **OR** **0.3 ≤ Graham's Ratio <0.5**

Longwall Return

CO Make

Using the more conservative 0.5 Graham's ratio from Moranbah North test results at approximately 60°C and assuming an oxygen deficiency of 0.3, solving for the carbon monoxide concentration gives a value of 15ppm. This represents an increase in carbon monoxide by a factor of 2.2 compared with between 2.7 and 3 observed in small scale testing. In 75m^3/s 15ppm would result in a CO Make of 67.5/l/min.

Considering that the aim of Level 1 is to identify that conditions are no longer normal and as pointed out already, all of the coal involved in small scale testing reaches the same elevated temperature a more conservative approach is recommended. An upper limit for Level 1 of 50l/min would represent an increase in raw carbon monoxide to just over 11ppm (almost double the upper normal limit). With an oxygen deficiency of 0.3 this would represent a Graham's ratio of just under 0.4. This is line with the intent of Level 1 triggers and as such it is recommended that the upper Level 1 limit for CO Make be set at 50l/min.

Graham's Ratio

It is recommended that the more conservative test results from Moranbah North be used for the setting of Graham's ratio at Grosvenor. The latest testing for Moranbah North returned a value of 0.54 at 64°C. The average at this temperature including the previous two tests (also conducted at Simtars) was 0.47. Therefore a Graham's ratio upper limit of 0.5 is recommended for Level 1.

Carbon Monoxide:Carbon Dioxide Ratio

It is not recommended that CO/CO_2 trigger a response above that for Level 1 and therefore a value of greater than 0.2 is recommended with no upper limit set.

Goaf Stream

Carbon Monoxide

Applying a factor of two to the recommended upper normal limit for carbon monoxide returns a value of 200ppm. A factor of two is in line with increases observed in small scale testing over the targeted temperate range. As seen in Figure 35 the oxygen deficiency seen in the goaf stream at Moranbah North was regularly between 2 and 4. This oxygen deficiency and a carbon monoxide concentration of 200ppm would result in Graham's ratio values in the range of 0.5 and 1. Even though a Graham's ratio of 1 is too high for the objectives of this trigger level, having a standalone Graham's ratio trigger covers the situation of elevated carbon monoxide at times of lower oxygen deficiencies. This means that neither safety nor assets are compromised. As such it is recommended that the upper limit for carbon monoxide in the goaf stream be set at 200ppm.

Graham's Ratio

For the same reasons used to recommend an upper Level 1limit of 0.5 for the longwall return, it is recommended that the goaf stream upper limit for Level 1 be set at 0.5.

Active Goaf Seals

Carbon Monoxide

The same logic applied to setting the upper Level 1 limit for goaf stream samples applies to active seal samples and as such an upper limit of 200ppm carbon monoxide is recommended.

Graham's Ratio

As for the longwall return and goaf stream sample locations, an upper limit of 0.5 for Graham's ratio is recommended for active seals.

3.2.3 Level 2

Level 2 triggers indicate that the results are now not only in excess of normal but are increasing or have increased to a point that warrants effective mitigation (any previously implemented controls may not be effective) so that the situation does not progress to the point of an unacceptable level of risk (including business risk). Results in this trigger level should not present an unacceptable level of risk to workers safety. However breaching the upper limit signifies indication that if an explosive atmosphere existed, the spontaneous combustion activity has progressed to a point considered to be a potential ignition source so conservative limits must be used. The setting of the upper limits for this level is critical as it establishes the thresholds for Level 3 which indicates that the situation is not under control and has progressed to the point of being an unacceptable level of risk.

A key requirement for this level is the formation of a team to monitor the situation and determine and implement the most appropriate controls. It must be noted that many mines call for the formation of an IMT at this level. However it is the author's view that the normal emergency response IMT may not be the most appropriate team to deal with a spontaneous combustion event, particularly at the early stages. A dedicated spontaneous combustion management team may be more appropriate.

Due to the difficult nature in defining and identifying most physical indicators it is recommended that they be included as a trigger for Level 2, and not Level 3 with the exception of smoke coming from the goaf. MDG1006 and the Moura No. 2 Warden's Inquiry both make mention of the importance of physical indicators. As a trigger for Level 2 the formation of a spontaneous combustion management team to investigate would be required. For example, smell as important as it is to identifying a spontaneous combustion event is impossible to quantify and this presents problems with triggering withdrawal. Once withdrawn, how does ongoing monitoring of this parameter continue? Instead gas monitoring data would be relied on to assess the situation. It is important however that reports of physical signs be investigated and not dismissed. For this reason sweating, smell, heat and haze (confirmed by ERZ Controller) have been added to all of the sample locations at this level.

The Trigger Level to initiate a Level 2 Response is greater than the upper limit for Level 1 which has already been discussed. The aim in setting the upper limit triggers for this level is to match indicators with test data at approximately 100^{o}C for reasons already discussed. From laboratory testing the Graham's ratio was 1.3 at 100^{o}C for the Grosvenor sample and 1.79 at 109^{o}C for the Moranbah North sample. The carbon monoxide concentration increased by a factor of approximately 10 between 42°C and 100°C for the Grosvenor sample and by a factor of 28 for the Moranbah North sample between 48°C and 109°C. The factor of increase between approximately 60°C and 100°C was nearly four for the Grosvenor sample and just over nine for the Moranbah North sample.

Although 1ppm of ethylene was not detected in small scale testing until the temperature reached 100°C, trace amounts were detected from just below 90°C. There have been issues throughout the industry relating to trace amounts of ethylene being detected without any other indicators of elevated temperature. The detection limits of the gas chromatograph and issues with signal to noise ratios become critical with this parameter.

It is recommended that any ethylene that is at the lower detection limits of the gas chromatograph; between 0ppm and 1ppm, activate Level 2 (action for which includes formation of a spontaneous combustion review team to conduct investigation). Although the absolute presence of ethylene has often been used as an indicator of elevated temperature, this will eliminate any issues with false reporting of ethylene at the GC's detection limits. This does not compromise safety because if real, the associated carbon monoxide would be generated and Level 3 would be triggered based just on carbon monoxide.

Issues related to incorrect detection of ethylene at concentrations greater than 1ppm can be averted by linking the ethylene with a significant amount of carbon monoxide (generally at least that required to trigger a Level 2 response). If less than 1ppm ethylene is detected or greater than 1ppm is detected but the CO indicator is less than a Level 2 response then it is a Level 2 Trigger. The presence or detection of ethylene always warrants investigation and this way the formation of a review or incident management team will be initiated and such an investigation can begin without evacuating the mine and yet not compromising the safety of mine workers as standalone carbon monoxide triggers have been recommended.

Recommended trigger levels are summarised in Table 6.

Table 6: Recommended Level 2 Triggers

Level	Level 2 Response
Longwall Return	**50l/min ≤ CO Make < 150l/ min** **OR** **0.5 ≤ Graham's Ratio < 1** **OR** **0ppm < Ethylene <1ppm OR > 1ppm but CO Make < 50l/min** **OR** **Sweating, smell, heat or haze (confirmed by ERZ Controller)**
Goaf Stream	**200ppm ≤ Raw Carbon Monoxide < 800ppm** **OR** **0.5 ≤ Graham's Ratio <1** **OR** **0ppm < Ethylene < 1ppm OR > 1ppm but CO < 200** **OR** **Sweating, smell, heat or haze (confirmed by ERZ Controller)**
Active Goaf Seal	**200ppm ≤ Raw Carbon Monoxide < 800ppm** **OR** **0.5 ≤ Graham's Ratio < 1** **OR** **0ppm < Ethylene < 1ppm OR > 1ppm but CO < 200ppm** **OR** **Sweating, smell, heat or haze (confirmed by ERZ Controller)**

Longwall Return

CO Make

Particularly for a new mine it is appropriate to use the more conservative results from small scale testing. For the Grosvenor sample an increase in carbon monoxide by a factor of approximately 10 was seen between 42^{o}C and 100^{o}C and a factor of four between 60^{o}C and 100^{o}C. Applying these factors would result in upper limits of 300l/min and 200l/min respectively. These values are not considered conservative enough. Applying a factor of three (compared to four from small scale testing) to the upper Level 1 limit would return a CO Make of 150l/min. In a ventilation quantity of 75m^3/s, that would equate to a raw carbon monoxide concentration of 33ppm. Assuming an oxygen deficiency of 0.3 (conservative at this level of oxidation) this would return a Graham's ratio of just over 1. It is therefore recommended that the upper CO Make limit for Level 2 be set at 150l/min.

Graham's Ratio

In the laboratory testing all of the coal is heated to the test temperature which is not the case in a heating in a goaf. As a result Graham's ratio may be underestimated because coal not at the same elevated temperature is not converting the oxygen into carbon monoxide with the same efficiency. For this reason a value lower than that from testing is recommended. Again using the more conservative small scale testing results and knowing that all of the coal generating the results was at the same temperature, it is recommended that based on the Grosvenor sample returning a Graham's ratio of 1.3 at 100^{o}C, the upper limit for Level 2 for Graham's ratio be set at 1.

Ethylene

It is unlikely to detect ethylene from a heating in a tailgate return unless a significantly intense spontaneous combustion event is occurring. This is because of the dilution that occurs. The critical aspect to inclusion at this trigger level is the formation of a review team that can investigate the reason behind the detection of the ethylene and if required elevate the classification of the situation. As discussed above, the appropriate quantities for this level are between 0 and 1ppm or concentrations greater than 1ppm but where less than 50l/min CO Make is measured. The first trace of ethylene (less than 1ppm) identified in small scale testing also had 82ppm of carbon monoxide. 82ppm of carbon monoxide in 75m^3/s ventilation would give a CO Make of 369l/min.

Goaf Stream

Carbon Monoxide

Although a factor of just three was considered as appropriate for the applying to the upper Level 1 CO Make to determine an appropriate upper Level 2 limit, it may not be appropriate for the goaf stream. Likely composition of the goaf stream prior to commencement of longwall operations is difficult to predict. Applying a factor of just three may result in premature withdrawal from the mine. Instead it is recommended that the small scale testing factor of four from the Grosvenor sample be used. This is still conservative when compared with the factor of over nine for the Moranbah North sample. Additionally a standalone Graham's ratio is recommended that will identify any intense heating regardless of the absolute carbon monoxide concentration generated. The combination of raw carbon monoxide and Graham's ratio adequately covers the likely scenarios that could eventuate. It is recommended that the upper limit for Level 2 be set at 800ppm carbon monoxide.

Graham’s Ratio
For the same reasons given for the recommended longwall return, an upper Graham’s ratio limit for Level 2 of 1 is recommended.

Ethylene
Ethylene should be included for this location in this level. The appropriate quantities for this level are between 0 and 1ppm or concentrations greater than 1ppm but where less than 200ppm of carbon monoxide is detected (unlikely that 1ppm of ethylene would be detected without finding more than 200ppm carbon monoxide based on gas evolution testing). The critical aspect to this trigger level is the formation of a spontaneous combustion review team that can investigate the reason behind the detection of the ethylene and if required elevate the classification of the situation.

Active Goaf Seals
Carbon Monoxide
The same logic applied to the setting of the upper limit for the goaf stream can be applied to the active goaf seals and as such an upper limit of 800ppm carbon monoxide is recommended as the upper Level 2 limit. The combination of raw carbon monoxide and Graham’s ratio adequately covers the likely scenarios that could eventuate behind an active seal.

Graham’s Ratio
As for the longwall return and goaf stream, an upper limit for Level 2 of 1 is recommended for Graham’s ratio.

Ethylene
Ethylene should be included for this location in this level for the same reasoning as for the goaf stream. The appropriate quantities for this level are between 0 and 1ppm or concentrations greater than 1ppm but where less than 200ppm of carbon monoxide is detected (unlikely that 1ppm of ethylene would be detected without finding more than 200ppm carbon monoxide based on gas evolution testing). The critical aspect to this trigger level is the formation of a spontaneous combustion review team that can investigate the reason behind the detection of the ethylene and if required elevate the classification of the situation.

3.2.4 Level 3

TARPs are meant to define clear actions. There was much discussion in the Moura No. 2 inquiry about leaving decisions to withdraw to those in charge. The Warden’s report included “There was no protocol at Moura No 2 for the withdrawal of persons from the mine in response to potential dangers. This left consideration of questions of withdrawal to those officials who happened to be on duty at any particular time. In the actual event the question of withdrawal was immersed in uncertainties with regard to the state of the mine and, in any case, appeared to have been left largely to the opinion of the middle ranking official who happened to be on duty. Any attempts that official made to obtain guidance from more senior management were not fruitful and, ultimately, any question of staying out of the mine was left to the workforce. This situation is totally unacceptable.

It is recommended that mines be required to develop and implement protocols, as a statutory requirement, for the withdrawal of persons when conditions warrant such action."

The recommended trigger level values are greater than the recommended upper Level 2 values discussed already. As discussed the idea of Level 3 is to have a level that triggers the withdrawal of personnel from underground when an unacceptable level of risk exists. In this situation an unacceptable level of risk is when there is the potential for an explosion, so a heating has progressed to a point considered sufficient to be an ignition source and there is an explosive gas mix in the goaf (assumed to be possible at all times). Note that the triggers need to be set such that the realisation of the risk is not imminent but that sufficient time is available for a controlled withdrawal. As already discussed this point has been aligned to 100°C. Smoke coming from the goaf is included as a Level 3 trigger as it signifies that the temperature is well in excess of 100°C and is one of the most easily identified physical indicators.

Level 3 triggers are summarised in Table 7.

Table 7: Recommended Level 3 Triggers

Level	Level 3 Response
Longwall Return	**CO Make ≥ 150l/min OR Graham's Ratio ≥ 1 OR Ethylene ≥ 1ppm AND CO Make ≥ 50l/min OR Smoke (coming from goaf)**
Goaf Stream	**Raw Carbon Monoxide ≥ 800ppm OR Graham's Ratio ≥ 1 OR Ethylene ≥ 1ppm AND CO ≥ 200ppm OR Smoke (coming from goaf)**
Active Goaf Seal	**Raw Carbon Monoxide ≥ 800ppm OR Graham's Ratio ≥ 1 OR Ethylene ≥ 1ppm AND CO ≥ 200ppm OR Smoke (coming from goaf)**

4 Recommendations

- Implement sampling regime appropriate for longwall mining.
- Review data on at least a weekly basis to ensure that assumptions made and normal range set are appropriate.
- Review data mid panel and completion of panel to ensure TARP triggers remain appropriate.
- LW return triggers for CO make and Graham's ratio not triggered by GC results.
- Determine the usefulness of CO/CO_2 ratio at Grosvenor as an early indicator considering seam gas content contribution to concentration likely to be greater than that from oxidation.
- Determine confirmation requirements of analysis for trigger activation based on risk management principles and clearly identify them in the TARP (eg a Level 3 trigger should not need to wait hours for confirmation samples to be collected and analysed if an unacceptable level of risk has been identified).
- Use of inertisation triggers formation of spontaneous combustion response team to evaluate influence inertisation is having on how representative sampling is, interpretation of data and appropriateness of existing trigger levels.
- Include trigger (not separate TARP) based on slower than expected longwall retreat.
- Use data collected and reviewed midblock to establish triggers for sealed and newly sealed goaves in time for sealing submission to inspectorate.

5 Assumptions

- Background data from Moranbah North is similar to that for Grosvenor.
- The samples submitted for spontaneous combustion propensity testing from Moranbah North and Grosvenor and results generated are representative of the coal seam being mined and left in the goaf at Grosvenor.
- Grosvenor's gas monitoring regime is adequate to identify the onset of any spontaneous combustion (i.e. sample location and frequency).
- Interpretation is not solely based on hitting triggers and that data is reviewed for rates of change and any anomalies.
- If inertisation is used as a control its influence on ratios and representative sampling will be considered and trigger levels adjusted where required.
- If indicators are confirmed to be in Trigger Level 1, implementation of controls does not have to wait until Level 2 Trigger reached.
- Graham's ratio values with oxygen deficiency less than 0.3 used with caution.
- Gas chromatograph results are reviewed and compared with TARPs.