

Best Practice Guidelines for the Management of Hot Holes in Opencast Coal Mines



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Date	9 June 2022

Guideline intent

This document is a compilation of Best Practice Guidelines (BPG) for managing hot holes in opencast coal mines. The main objectives of this BPG are:

- To provide some guidance on some of the best practices that can be utilised by opencast coal mines to identify hot holes.
- To recommend some of the best practices for measuring and monitoring hole temperatures.
- To recommend some of the best practices for the management of hot holes.

The BPG could be used as a reference document by relevant South African surface coal mines to review and enhance their Standard Operating Procedures (SOPs) for the management of hot holes. Moreover, the BPG may also be used as a reference document by relevant international open cast coal mines. In both instances, efforts must be made to ensure that the different recommendations are applicable and relevant to specific site conditions. The BPG is for open cast coal mines, particularly those with hot holes and is intended to be used by mining personnel such as drilling crews, blasters, blasting assistants, blasting foremen, mine overseers and production managers. This BPG is a compilation of knowledge gathered from various SOPs for the management of hot holes in different mines and experiments that were conducted at two South African open cast coal mines. The guide may have gaps and omissions, therefore it should be reviewed and revised regularly.

Guideline layout

The guideline is structured into the following sections:

- Introduction.
- Methodology used to develop the BPG.
- Guidelines for managing hot holes.

Moreover, the appendices on this guideline are milestone reports that were compiled as part of the project to develop the BPG. Appendix A is a review of local and international temperature measuring and monitoring devices that may be applicable to hot holes.

Appendix B details the results of SOP reviews; field observations and monitoring of hot hole management practices; and tests conducted on hot hole management tools such as (Polyvinyl chloride) PVC, foam expander plugs and gas bags.

Disclaimer

Reasonable efforts were made to ensure that the data and information contained in this guideline are correct. However, the Coaltech Research Association, and Council for Scientific and Industrial Research (CSIR) provide no warranties on the completeness or accuracy of the information and shall not be held liable for any loss or damage that may occur directly or indirectly through using, or relying on, the contents of this guideline. Users should consider the guideline to be a reference guide on accepted best practice at the time of publication. The guideline is not intended to replace SOPs, regulatory requirements, and the need for professional advice on the management of hot holes at individual opencast coal mines. The guideline should be reviewed and revised, so that new ideas can be incorporated, and gaps filled as more information, new practices and new technologies become available.

Acknowledgements

The researchers would like to acknowledge the financial support received from the Coaltech Research Association to conduct the project titled “The Management of Hot Holes in Opencast Coal Mines”, whose output is this BPG. We would also like to thank the following stakeholders who contributed to the development of this BPG:

- All coal mining companies that provided data, study sites, and testing accessories and instruments that were used in the study.
- Coaltech Steering Committee and technical personnel from Coaltech member mines for their technical support and guidance during the execution of the project.

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List of abbreviations

AECI	African Explosives and Chemical Industries
ANFO	Ammonium nitrate and fuel oil
BME	Bulk Mining Explosives
BPG	Best Practice Guideline
COP	Code of Practice
CSIR	Council for Scientific and Industrial Research
DMRE	Department of Minerals Resources and Energy
LCD	Liquid Crystal Display
LED	Light-emitting diode
MMU	Mobile Mixing Unit
MSIAC	Munitions Safety Information Analysis Centre
NATO	North Atlantic Treaty Organisation
OHS	Occupational Health and Safety
PPE	Personal Protective Equipment
PVC	Polyvinyl chloride
SOP	Standard Operating Procedures
STANAG	Standardisation Agreement
UN	United Nations

Glossary

Term	Definition
Bhoboza hole	Shot hole (drilled on surface) that has holed through to old underground workings (also known as breakthrough holes)
Shot hole	Drilled hole that has been charged or is intended to be charged with explosives
Stemming	A process of filling a shot hole with inert material on top of explosives to prevent the escape of gases when explosives are detonated
Venting hole	Shot hole that releases smoke or gas due to the atmospheric air that goes in the hole
°C	Degrees Celsius
UN 8C (Koenen Test)	A test used to determine the sensitivity of a candidate ammonium nitrate emulsion or suspension or gel, intermediate for blasting explosive, to the effect of intense heat under high confinement (A-P-T Research Inc., 2022)
UN 8D (Vented pipe test)	A test used to assess the effect of exposure of a candidate for “ammonium nitrate emulsion or suspension or gel, intermediate for blasting explosive” to a large fire under confined, vented conditions (ET Users Group, 2022)
NATO Standardisation Agreement (STANAG) 4240	A test used for fast heating, which includes three acceptable test methods; a large pool fire, a mini pool fire and a fuel burner fire (Munitions Safety Information Analysis Centre (MSIAC), 2018)
STANAG 4382	A test used to assess the reaction, if any, of munitions and weapon systems to a gradually increasing thermal environment (Baker, 2018)

1. Introduction

1.1. Introduction

Mining over old underground workings presents the risk of intercepting hot ground or underground fires during the drilling process. The drilled holes become an ingress for oxygen and an outlet for noxious gases and heat generated by spontaneous combustion in the previous underground bord and pillar coal mines (Figure 1).

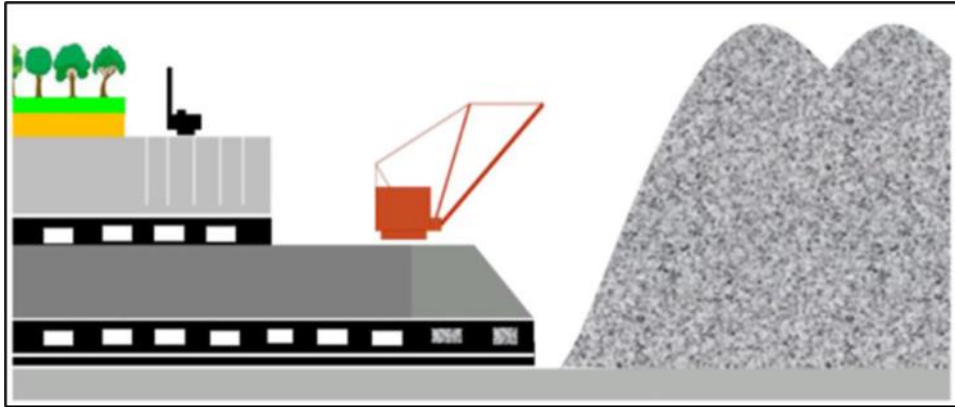


Figure 1. Mining over old underground bord and pillar workings (Ngwenyama & de Graaf, 2021)

Working in such environments, which involves charging the holes with explosives, exposes workers to hazards such as:

- Hot air exhausted from underground.
- High concentration of noxious gases such as carbon dioxide, carbon monoxide and sulphur dioxide.
- Premature detonation due to:
 - Temperature increase which affects the chemical composition of explosives products.
 - Softening and/or melting of initiating system components.

Premature detonation may lead to injuries, loss of life, damage to equipment, and the destruction of infrastructure. Moreover, the high temperatures may reduce the effectiveness of the explosives products, causing suboptimal blasts. Mining in the ground containing hot holes poses a significant safety risk to the workforce, and it is critical for surface coal mines to have sound hot hole management practices, in order to mitigate all associated risks. Table 1 shows examples of some local and international hot holes and/or reactive ground-related incidents at different mine sites.

Table 1. Examples of local and international incidents caused by hot holes and/or reactive ground.
Adapted from (AEISG, 2020)

Year	Location	Incident description
2020	South Africa	Premature detonation in a hot hole
2019	South Africa	Premature detonation in a hot hole
2018	South Africa	An uncontrolled detonation of two blast holes caused by an extreme hot hole
2016	Indonesia	A melted booster in a hot hole
2014	Indonesia	Premature detonation in a hot hole and reactive ground area
2014	Chile	Premature detonation in a hot hole
2014	Canada	Mass detonation in a hot hole area
2014	Australia	Melted downlines in a hot hole and reactive ground area.
2013	Chile	Premature detonation in a hot hole
2013	Australia	Premature detonation in a hot hole
2013	Australia	Melted downlines in a hot hole area
2011	Mongolia	Premature detonation in a hot hole and reactive ground area
2010	Australia	Premature detonation in a hot hole and reactive ground area
2010	South Africa	Mass premature detonation in a hot hole area
2009	Australia	Premature detonation in a hot hole
2009	South Africa	Premature detonation in a hot hole

1.2. Regulation on hot holes

Surface coal mining operations in South Africa are often executed on virgin ground and/or above old underground workings. The shot holes drilled are either cool or hot. Cool holes have in-hole temperatures below 40°C. According to the Department of Minerals Resources and Energy (DMRE), hot holes are defined as drilled shot holes that have an in-hole ambient temperature of 40°C or above, or show a temperature increase of 3°C or more during monitoring (MHSC, 2019). The regulations do not provide some guidance/clarity on whether holes with a temperature less than 40°C should be classified as hot holes if they “show a temperature increase of 3°C or more during monitoring”. For example, if the initial hole temperature was 30°C and the recorded second hole temperature reading during monitoring is 35°C (i.e., 5°C increase in temperature). Should this hole be classified as a hot hole or not?

During the field tests, the research team noted that some holes with initial low hole temperatures (say 30°C), could experience significant temperature increases during monitoring. In some instances, the measured temperatures of these holes ended up

exceeding 40°C. To this end, the researchers are recommending that any holes that “show a temperature increase of 3°C or more during monitoring” should be considered as “potential” hot holes, even if the temperatures are below 40°C. This could assist the mines to reduce the risks associated with those cold holes showing initial temperatures below 40°C, but eventually undergoing significant temperature increases until they become hot holes. Future studies could focus on trying to understand the evolution of hot holes and possibly define the cut-off temperature on which the “temperature increase of 3°C or more during monitoring” should apply. There is also a need to consider aligning the definition of hot holes in the regulations with the recommendation provided above. Moreover, it will also be important to continuously update the definition of hot holes as new knowledge becomes available.

1.3. Sources of the heat found in hot holes

The main source of heat found in hot holes is from the spontaneous combustion of coal in old underground workings. Spontaneous combustion in coal mines has been researched and reported on extensively both locally and internationally by authors that include Eroglu (1999), Stenzel (2002), Eroglu (2003), Otter et al. (2005), Uludag (2007), Phillips et al. (2011), Sloss (2015), Genc and Cook (2015), Onafide and Genc (2019) and Ngwenyama and de Graaf (2021). The research covered a wide scope of spontaneous combustion aspects, including the causes, prevention, prediction, and monitoring of spontaneous combustion in different mining areas. Although the previous research applies to varying spontaneous combustion sources such as spoil dumps, coal stockpiles, underground coal mining face, goaf zones of longwall mining methods and open pit highwalls, the concepts for managing spontaneous combustion are similar and relevant to the management of hot holes in surface mines located over old underground workings. The key concepts of spontaneous combustion are summarised as follows (Eroglu, et al., 1999; Uludag, 2007; Muswellbrook Coal Company Limited, 2010; Phillips, et al., 2011; Genc & Cook, 2015; Oageng, 2016; Onafide & Genc, 2019):

- Spontaneous combustion (self-heating or autogenous ignition (Uludag, 2007)) occurs without a source of heat. When coal is oxidised, heat is generated in this exothermic reaction. Dissipation of the heat depends on factors such as the air velocity and the thermal conductivity of the coal and host rock. The degree of combustion is a function of intrinsic factors such as coal composition, the presence of pyrites and moisture content; and extrinsic factors that include atmospheric

pressure, the relative humidity and the presence of faults and weak or disturbed strata conditions.

- Spontaneous combustion and the subsequent burning are sustained by three elements, namely oxygen, fuel and heat. Thus, strategies used in the management of spontaneous combustion should focus on depriving coal (fuel) of oxygen, minimising exposure of coal (fuel) to oxygen, and insulating the coal (fuel) from heat.

The other source of the heat generated in hot holes is from the reactions between reactive ground and some ingredients of explosives products. The term reactive ground refers to the ground that contains, mainly, iron and copper sulphides, and to a lesser extent coal sulphides. This ground undergoes a spontaneous exothermic reaction after it comes into contact with nitrates of ammonium, calcium and sodium (found in explosives products) and the reaction involves the chemical oxidisation of the sulphides releasing heat (Sharma, 2010; White, 2018; AEISG, 2020). According to Sharma (2010) and White (2018), the temperature rise is unstable and can be as low as 2°C or as high as several hundred degrees. The reaction in a charged drill hole is violent and may result in the premature and uncontrolled detonation. The reactive ground also leads to the liberation of toxic nitrous and sulphide fumes, which have negative impacts on the health of workers.

The spontaneous combustion of coal leads to ground that has elevated temperatures. When the ground is drilled, the holes are found to be hot. Additional risk is encountered after charging the hot holes if the ground is reactive (containing sulphides). Reactive ground leads to elevated temperatures in the holes when these sulphides react with the nitrates of some explosives products. Therefore, the risk associated with the hot holes should be continuously assessed and managed. The process of assessing and managing the risk includes the use of temperature measurement and monitoring devices, hot hole management tools, and selecting and using emulsion products that are specific to the conditions at the mine.

1.4. The management of areas with hot ground

The literature revealed that the most effective means of managing areas with hot ground and controlling spontaneous combustion is to deprive the fuel (coal) of oxygen. Therefore, most strategies aim to prevent air from coming into contact with any coal that

is prone to spontaneous combustion. Alternatively, the time that the coal surface is exposed to air should be minimised to reduce the risk of spontaneous combustion. Methods used to reduce spontaneous combustion, particularly when mining over old underground workings, include the following:

- **Cooling agents** – High pressure water and cooling agents such as Pyrocool are used to douse surface fires. These cooling agents are also used to reduce the temperature in hot holes. However, due to the difficulty in accessing the source of the combustion, fires usually re-ignite, thus, this method is used as a temporary measure or quick-win solution (Eroglu, 2003; Phillips, et al., 2011; Sloss, 2015; Ngwenyama & de Graaf, 2021).
- **Sealing agents** – This involves combining an inhibitor, such as calcium chloride, with a binding agent and a filler such as bentonite to starve coal of oxygen thus reducing spontaneous combustion. The disadvantage of these sealing agents is that they may be unstable and an expensive solution to seal off large areas like those found in surface coal mines (Eroglu, 2003; Phillips, et al., 2011; Sloss, 2015; Ngwenyama & de Graaf, 2021).
- **Inert gas** – This involves the use of inert gases such as nitrogen and carbon dioxide to flush out combustible gases. The method is expensive and impractical to use in extensive mining areas (Eroglu, 2003).
- **Dozing over** – This involves dumping of sand on the highwall using a dozer, as shown in Figure 2, to close-off openings into the old workings. This has to be done carefully and completely to avoid any remaining venting (Eroglu, 2003).



Figure 2. Dozing of a highwall with soil (Eroglu, 2003)

- **Buffer blasting** – Use of explosive energy to heave (upwards direction) the overburden, collapsing old underground pillars, and sealing bords or roadways to close-off old ventilation routes and voids that supply oxygen to the coal. This method of blasting also improves the stability of the site mining block (Figure 3) (Eroglu, 2003) (Phillips, et al., 2011; Sloss, 2015; Ngwenyama & de Graaf, 2021).

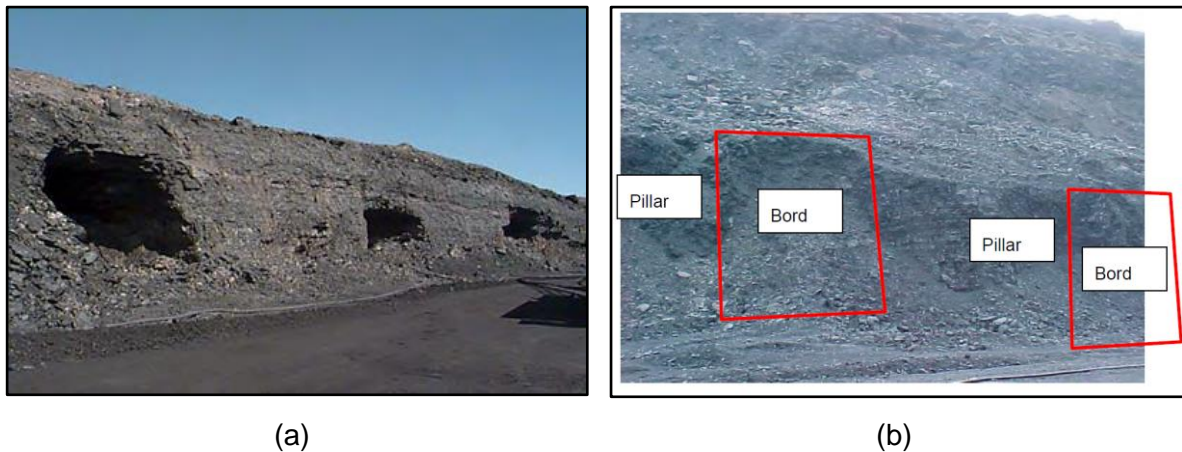


Figure 3. Coal operation without buffer blasting (a) and with buffer blasting (b) (Phillips, et al., 2011)

- **Cladding** – Placing weathered overburden or topsoil over highwalls to limit airflow into the old underground workings through voids (Figure 4). This method may lead to dilution (Eroglu, 2003; Phillips, et al., 2011; Sloss, 2015; Ngwenyama & de Graaf, 2021).



Figure 4. An area of ground after cladding with sand (Eroglu, 2003)

- **Buttress blasting** – This is a throw or cast blasting method used to seal off voids in the highwalls (Figure 5). Similar to buffer blasting, this method uses explosive energy

to cast material, towards the highwall. The method may result in dilution in the re-handling of material (Eroglu, 2003) (Sloss, 2015; Ngwenyama & de Graaf, 2021).

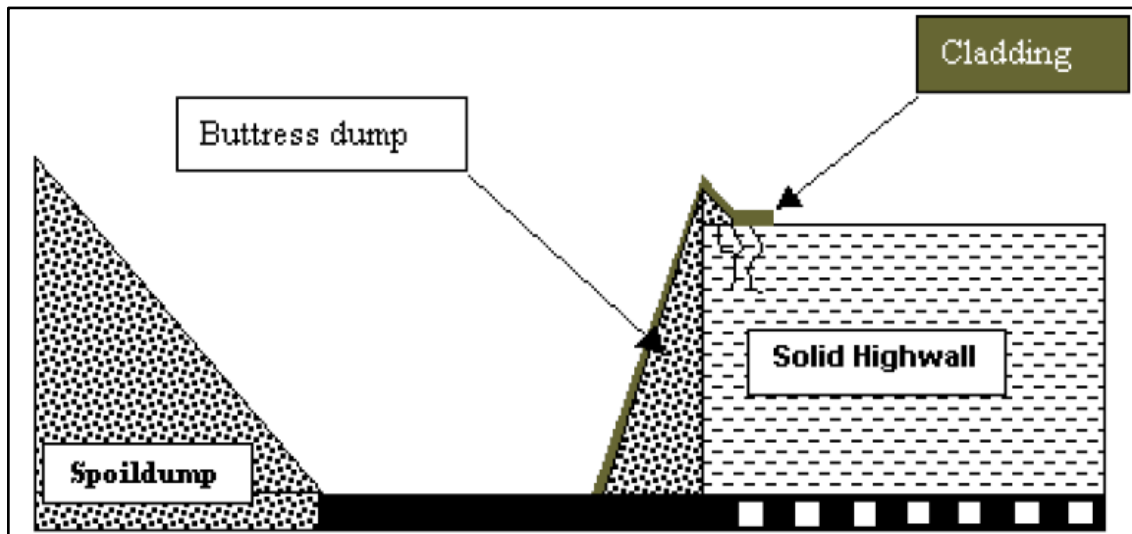


Figure 5. Buttress blasting and cladding applied to a highwall (Eroglu, 2003)

- **Just-in-time drilling** – The method is implemented to ensure that newly uncovered coal is excavated immediately after exposure to the air (Sloss, 2015).

It should be noted that every mine is unique and therefore, there is not a single solution to the risks associated with mining in areas with hot ground. Furthermore, mining environments and situations change overtime and so should the associated risk assessments, management plans and solutions to minimising the risk of spontaneous combustion. Importantly, managing spontaneous combustion (large-scale risk management) through prediction, prevention and control measures provides a solid foundation for the management of hot holes (small-scale risk management) that are encountered on a mining block after drilling.

1.5. The management of hot holes

There has not been considerable literature that focuses solely on the management of hot holes. Available literature, as aforementioned, focused on the management of spontaneous combustion, which is the source of the heat found in the drilled holes. The strategies used in the management of spontaneous combustion, although they are mostly used as a primary risk management measure in large scale areas, are thus, applicable to the management of hot holes.

Local research and developments have been done mainly at mine level or by explosives manufacturers independently and/or in collaboration with the mines. Tests conducted on emulsion can be classified as small scale or large-scale tests. Table 2 shows some characteristics of the two tests. The tests are based on standards such as the Koenen test and the NATO (North Atlantic Treaty Organization) STANAG (Standardisation Agreement) 4240 (Munitions Safety Information Analysis Centre (MSIAC), 2018; A-P-T Research Inc., 2022). In general, small-scale tests, as suggested by the name, use smaller apparatus and lower quantities of explosives compared to large-scale tests. The result is that large-scale tests produce more realistic test results due to explosives product quantities like those used in normal blast holes.

Table 2. Differences and similarities between small-scale and large-scale emulsion tests

Parameter	Small scale tests	Large scale tests
Use	<ul style="list-style-type: none"> To determine transport safety characteristics 	<ul style="list-style-type: none"> To evaluate thermal behaviour and characteristics
Sample size	<ul style="list-style-type: none"> 5 g – 60 kg 	<ul style="list-style-type: none"> 60 g – 780 kg
Tests/Standards used	<ul style="list-style-type: none"> UN Test 8C (Koenen test) UN Test 8D (Vented pipe test) 	<ul style="list-style-type: none"> STANAG 4240 STANAG 4382

Rorke and Conradie (2022) reported on small-scale tests, conducted by Bulk Mining Explosives (BME), on bulk emulsion-based explosives to determine their sensitivity to heat. The tests involved heating a 1 kg sample of explosives in a pipe as shown in Figure 6. Tose (2022) reports on recent small-scale and large-scale tests conducted by African Explosives and Chemical Industries (AECI) to determine the behaviour of explosives in hot environments. Part of the test set up is depicted in Figure 7. For both tests, the following common observations were made (Table 3 and Table 4).

- The temperature at which white fumes start.
- The temperature at which the product is ejected.
- The temperature at which brown fumes are released.

- The temperature at which an event or eruption occurs.

Such test observations may be used by individual mines to classify the risk associated with hot holes in their respective conditions.



Figure 6. Set up for the tests on bulk emulsion-based explosives (Rorke & Conradie, 2018)

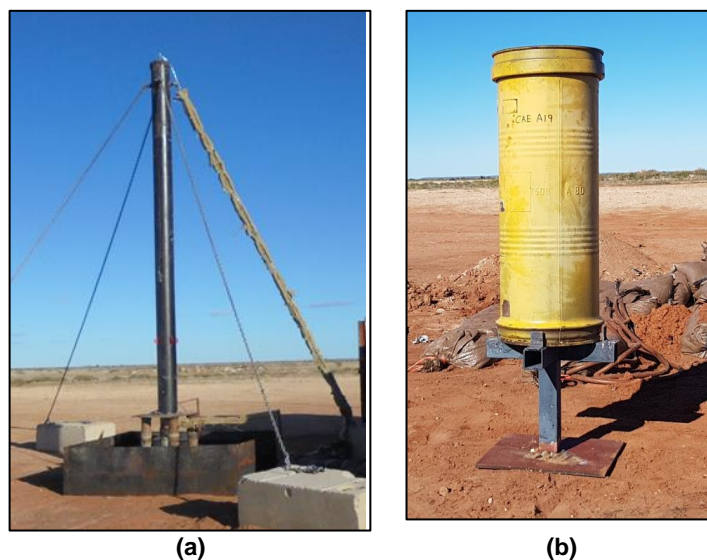


Figure 7. Part of the test set up for the UN 8C(a) and UN 8D (b) tests on hot hole emulsion (Tose, 2022)

Table 3. Observations during the BME tests on explosives products (Rorke & Conradie, 2018)

Temperature	Visual observations during tests
40°C	Minimum temperature of a hot hole as defined by the Mine Health and Safety Act (MHSA).
Up to 150°C	A rapid increase in temperature, with no visible emission from the test product. The product was raised to its boiling point, which was approximately 150.
150°C - 200°C	A slow, linear temperature increase for about 15 minutes in duration. During this time, steam was generated from the test samples. This represents the drying out of the test samples during which water consumed.
150°C - 320°C	A steep temperature increase was observed. Smoke with a burnt oil smell was generated from the test sample. At this point, there was probably no water in the product, and the oil was being burnt off. The temperature increased rapidly to a point of approximately 320 where a small event was registered.
At 320°C	A jump in temperature of 100 C (indicating that the event was an exothermic reaction) and a low intensity pressure wave from the sample that was recorded in Tests 2 and 3 by the air blast monitor. A peak value of 118 dB and a long duration between 1 and 2 seconds were recorded.

Table 4. Visual observations during the AECl tests on explosives products (adapted from (Tose, 2022)

Temperature	Visual observations during tests
40°C	Minimum temperature of a hot hole as defined by the MHSa.
80°C	Threshold temperature set as a risk mitigation measure to warn workers on a block of an increase in the temperature of the explosive product. Workers are required to evacuate the block at this temperature.
110°C	Grey-white fumes are produced as the water boils out of the reaction. These fumes may not be visible due to weather or atmospheric conditions. The fumes are like those produced during coal (fire) venting. At this temperature, the booster or detonating cord softens and melts.
130°C - 160°C	White fumes are observed.
140 - 220	Product ejection around the collar of the hole may be observed.
180°C	Orange-brown fumes are produced, signalling the release of noxious fumes. These fumes may not always be visible.
220°C - 260°C	The occurrence of an exothermic reaction and an event or eruption.

Internationally, the Australian Explosives Industry Safety Group Inc (AEISG) has, over the years, developed and updated the *Code of Practice for Elevated and Reactive Ground*. The aim of the code of practice (COP) is to assist in the prevention of premature detonation that may result from possible unwanted reactions between explosives products and/or accessories and the rock being blasted in hot and reactive ground (AEISG, 2020). The COP places emphasis on charging and blasting aspects such as the selection of explosives and accessories, the sleep time for explosives and shot design, in relation to hot and reactive ground. Figure 8 shows four conditions that are encountered on mining blocks as developed by AEISG (2020) and adapted by Tose (2022) to include heat and reactivity values. These conditions are based on heat

(temperature of the ground) and the reactivity of the ground, and are explained as follows (in the context of South Africa):

- Normal conditions refer to conditions in which the temperature and the reactivity of the ground or drill holes are less than 40°C and 1% respectively.
- Hot hole conditions are those that have a temperature of 40°C or more and a reactivity of less than 1%.
- Extreme blasting (hot and reactive ground) conditions are those that have a temperature of 40°C or more and a reactivity of more than 1%.
- Reactive ground conditions are those that have a temperature of less than 40°C and a reactivity of more than 1%.

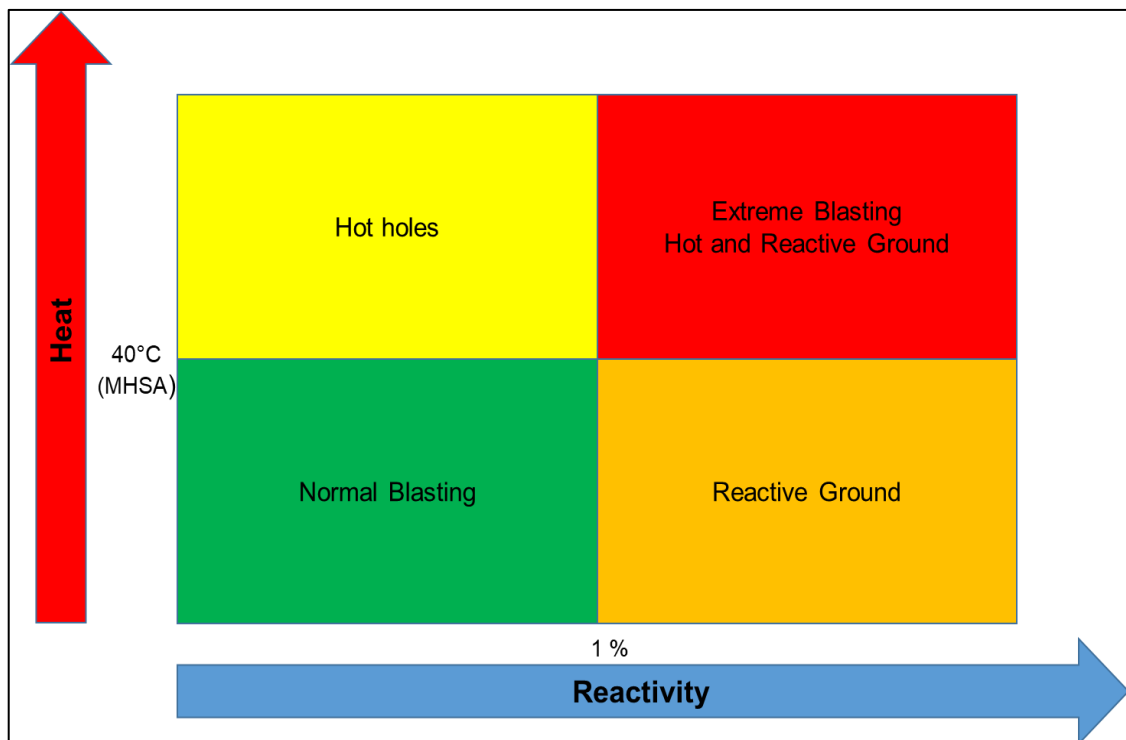


Figure 8. Four categories for the selection and use of explosives (AEISG, 2020; Tose, 2022)

According to AEISG (2018) and Tose (2022), it is crucial that mines consider these conditions in the selection of explosives products and accessories. The selection of a particular product should be accompanied by large-scale field tests at the respective mines to gain a full understanding of the exothermic reaction involved.

The main findings for the management of hot holes from literature are summarised as follows (Sharma, 2010; Phillips, et al., 2011; White, 2018; AEISG, 2020; Oates & Spiteri, 2021):

- Training and procedures – training, assessments after training, and periodic reassessments are encouraged for all personnel operating on the bench or those involved in the management of the personnel.
- Delineation of the blast zone – it is a proactive process conducted as part of the risk assessment, whereby a mine site or a mining block is divided into a hot hole area and a non-hot hole area so that succeeding activities such as charging are aligned (with respect to type of explosives and initiation systems used) accordingly.
- Hole temperature measurement and monitoring – this is the use of temperature measurement and temperature monitoring devices to identify holes that are hot and cold. Pursuant to this, the holes are periodically checked to determine whether they still display the initial temperature readings. This process assists in classifying the holes into particular categories defined by the mines and selecting the type of explosives products and hot hole management tools to be used in those particular holes.
- Hole loading sequence (on the pattern) – according to AEISG (2020), when charging in a hot hole area, it is advisable to load the holes closest to the initiation point first to allow for quick tying up and firing in the event of a change in the conditions on the bench. However, this loading sequence may lead to cross charging on a block, which may slow down productivity and may lead to workers getting stuck on one end of the block with no safe escape route. The AEISG (2020) also suggests that where practically applicable, the hottest holes should be loaded last to reduce the amount of time the explosives product is exposed to high temperature. The other loading sequence, as suggested by Tose (2022) is to load the hot holes from the farthest hole first and progress towards the entrance of the block to allow for an escape route that passes through uncharged hot holes in case of an event.
- Stemming – procedures at mines with hot holes and literature sources recommend that hot holes should not be stemmed to avoid a pressure build-up in the hole. Moreover, the addition of stemming material may limit visible signs (such as venting or the release of fumes from decomposing explosives) that a hole is undergoing heating and may increase the likelihood of detonation (Oates & Spiteri, 2021; Tose, 2022).
- Minimum explosive sleep times – literature findings recommend that the sleep time of products in a hot hole environment should be minimised to prevent the heating up

of explosives products, which may lead to product deterioration and a possible premature detonation.

- Minimising spillage – explosives product spillages on mining benches that have hot holes should be avoided to reduce the risk of the product decomposing if the bench is hot. Additionally, initiation system accessories should not come into contact with the spilt explosives as the possible decomposition of the explosive may cause the initiation system to degrade or detonate.
- Use of hot hole management tools – it was found that there are different types of hot hole management tools used at different mines. These tools include:
 - Temperature monitoring devices that monitor the change in temperature of emulsion loaded in a hot hole.
 - Temperature measurement devices (scanners, monitors, etc.).
 - Gas bags and foam expander plugs for sealing holes.
 - Cooling agents for reducing the temperature on hot ground.
 - Polyvinyl chloride (PVC) sleeves that act as a container for emulsion and a heat cushion to prevent the gain of heat from the hot hole.
- The selection of explosives and initiating system – it is encouraged that all explosives products and accessories should be selected based on the risk associated with the ground or conditions in which they would be used. Such conditions include normal blasting conditions, hot hole only, reactive ground only and hot hole and reactive ground conditions (Figure 8). The use of the selected explosives should follow large-scale field tests, preferably at the intended mining site. Regulations and the Technical Data Sheets should be followed to ensure that the products are used safely and correctly. Hot hole specific (inhibited) emulsion should be used for blasts in hot holes.

1.6. The need for a Best Practice Guideline

The mining sector continues to play a significant role in the socio-economic development of South Africa. Thus, sound management of occupational health and safety (OHS) is critical to protect the health and safety of the workforce, prevent damage to equipment and infrastructure, and guarantee the continued sustainability of the industry. Ripple benefits associated with good management of OHS at mines include improved cooperate image, increase in productivity and decrease in costs associated with OHS incidents such as litigation, insurance and compensation costs. Considering the risks and challenges associated with hot holes mainly because of spontaneous combustion,

the Council for Scientific and Industrial Research (CSIR) was tasked with investigating practices used for the management of hot holes in opencast coal mines and developing the BPG. The BPG for the management of hot holes has been developed to address the aforementioned challenges. This BPG provides practical guidelines that can be utilised by South African surface coal mines to enhance the management (eliminate or reduce) of the safety risks associated with hot holes. The guidance provided in this BPG will contribute to the industry's efforts to eliminate/reduce the safety risks associated with hot holes, thus contributing to sustainability of the mining industry and attainment of zero harm production (Zero Harm goal).

2. Methodology for the development of the BPG

Four tasks were completed in the development of the BPG. The tasks included a literature review on temperature measurement and monitoring devices, and tests on some of these devices and various hot hole management tools. The results obtained during the execution of the individual project tasks are provided in Appendix A (Milestone 2: Review of temperature monitoring devices for hot hole management) and Appendix B (Milestone 3: SOP reviews, on-block observations and experimentation at test site). The tasks are briefly described below:

- **A review of temperature measurement and monitoring devices** - A desktop study was conducted to identify available temperature monitoring and temperature measurement devices applicable to the management of hot holes. Some of these devices were tested at an open cast coal mine near Emalahleni.
- **An assessment of hot hole management SOPs** - An assessment of SOPs used for the management of hot holes, at three local open cast coal mines, was conducted. Through this assessment, tools, processes, and schedules of activities followed in the management of hot holes were identified. The sample size of the SOP assessment was limited by the few open cast coal mines experiencing the challenge of hot holes in South Africa.
- **On-block observations** - On-block observations followed the assessment of SOPs. The intent of the observations was to identify whether the procedures listed in the SOPs are implemented correctly and whether there were any newer innovations that were not listed in the SOPs. Furthermore, this task was conducted to gain a hands-on appreciation of how hot holes are dealt with on the ground by the mining personnel. Monitoring and observing was conducted at two opencast coal mines for a total duration of four weeks.
- **Experimentation at a test site** - Various experiments were conducted at a test site located in an opencast coal mine near Emalahleni. Temperature measurement and temperature monitoring devices were tested for parameters that include accuracy, durability, set-up time and audibility. Test protocols were developed and used to test the effectiveness of hot hole management tools such as foam expander plugs, gas bags and PVC sleeves. In addition to these tests, the project team monitored the evolution of the temperature of holes (in-hole ambient air and in-hole rock surface) on a block from the time the holes are drilled until prior to charging.

3. Best Practice Guidelines for Managing Hot Holes

Risk assessments are core to the management of hot holes. Risk assessments enable the identification of ground that has the potential to have hot holes, the classification and quantification of the risk and the generation of appropriate site and hot hole specific mitigation measures. The mitigating measures, procedures and processes that are developed following the risk assessments should be guided by the regulatory requirements for the management of hot holes. Risk assessment should be a continuous process, even during the implementation of the procedures. For example, monitoring the temperature of a hot hole from the time it is drilled until prior to drilling, enables personnel on the block to always be aware of the changing hole conditions and the associated hazards. This would then inform them of which mitigating measures to implement timeously. Part of managing the risk associated with hot holes involves selecting the appropriate temperature measurement and temperature monitoring devices, hot hole management tools, and explosives products and accessories. The selection of the products should be preceded by comprehensive site-specific tests.

This section describes best practice guidelines compiled from literature, experimental results, and engagements with mining industry stakeholders. The guidelines are divided into the following themes:

- Risk assessment.
- Identification of hot holes.
- Treatment of hot holes.
- Hot hole charging and blasting.

a. Risk assessment

Risk assessments should be conducted pre-emptively and continuously to ensure that the personnel on a hot hole block are always safe. Pre-emptive risk assessments should enable the identification of ground that has the potential of having hot holes when drilling eventually occurs. Such ground is mainly those mining blocks that are above old underground workings. The review of SOPs revealed that one mine considers all mining blocks located over old underground workings as carrying the risk of hot holes. This measure assists in identifying the hazards associated with these areas located over old underground workings and devising solutions to reduce the source of heat, which is mainly from spontaneous combustion. Thus, the primary step in such areas would be to implement some of the mitigating measures used for reducing spontaneous combustion

ahead of time before drilling commences in those areas. Such mitigating measures may include buffer and buttress blasting. Once the drilling and blasting crews commence work on areas with a risk of hot holes, the following risk assessments measures may be implemented to improve safety:

- Classifying the ground into hot and normal ground and choosing the appropriate and site-specific hot hole management tools, explosives products, and any other relevant accessories.
- Closing out the area before charging commences to reduce extra movement in and out and around the block.
- Reducing the number personnel working on a hot hole blast.

The legal appointee responsible for risk assessment should ensure that all the hazards have been identified and documented correctly. Furthermore, each worker should continuously scout for these hazards so that mitigating measures are implemented timeously if an event occurs.

b. Identification of hot holes

The identification of hot holes, after drilling, is a critical step in risk assessment. This is the stage at which the temperature of the holes is measured using a temperature measurement device(s) and the holes are classified into categories based on the mine-specific risk assessment matrices. Thus, the appropriate device should be used correctly to measure the accurate temperature readings across the depth of the hole. The failure to measure the temperature of a hole or recording an inaccurate reading may lead to the selection of the incorrect hot hole management procedure and tools. This may lead to unexpected immediate or down the line dangers such as premature detonations. It cannot be overstated that the measurement of the temperature of the holes on a block considered to be hot should be conducted immediately after drilling and periodically until charging commences. This ensures that any temperature changes in a hole are recorded and the necessary risk mitigating measures are implemented. Furthermore, assumptions should not be made in relation to the identification of hot holes. Each hole on a block should be treated individually and not assigned the temperature of an adjacent hole for example. Indicators such as venting or smoking may be used primarily to locate hot holes, however, these are not enough to detect the full risk associated with that particular hole.

Periodic temperature measurements

The periodic measurement of the temperature of the holes should be aligned with the drill and blast schedule. Since drilling precedes charging and blasting (by design), and unexpected operational constraints may deem it impossible to drill, charge and blast on the same day, there is a higher chance that the temperature of a hole changes overtime. Therefore, it is important to record the initial temperature of a hole immediately after drilling. This temperature recording becomes an input into the blast design and risk assessment for that mining block. If drilling, charging, and blasting do not occur on the same day, further temperature readings should be taken until charging commences so that the blast design and risk assessments are updated accordingly.

Selection of temperature measurement devices

There are various types of temperature measurement devices on the market. However, some of these devices are not suitable for the harsh hot hole mining environment. The different types of temperature measurement devices include thermocouples, thermometers, and infrared devices. These devices have distinct features and differ according to the method used to detect the temperature. The devices can be classified as detecting the temperature in-hole or from surface. Those temperature measurement devices that detect the temperature while placed in-hole are recommended as they give a more accurate temperature reading while immersed in the hole environment. An example of such an infrared device is shown in Figure 9 (a). Additionally, as stipulated in the regulation, using an in-hole device enables the generation of a profile along the depth of a hole. Using a device such as a laser gun (Figure 9 (b)), that detects the temperature of a hole from the surface is not advisable as it may give inaccurate temperature readings due to impediments such as the hole length, hole deviation and spot ratios.

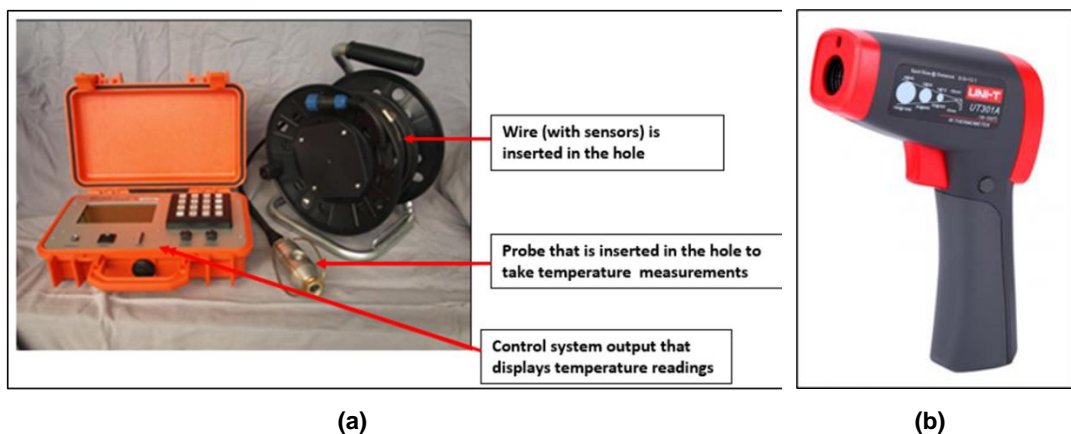


Figure 9. Two types of temperature measurement infrared devices

The other distinction between the temperature measurement devices is the heat source they measure. The source of heat that can be measured for temperature is either the rock surface or the air temperature. Thus, the devices should measure the in-hole rock surface temperature and/or the in-hole air temperature. In-hole infrared temperature probes (Figure 9 (a)) are an example of devices used to measure the temperature of the in-hole rock surface, whereas thermocouples, such as the k-type thermocouples shown in Figure 10, are used to measure the in-hole air temperature.

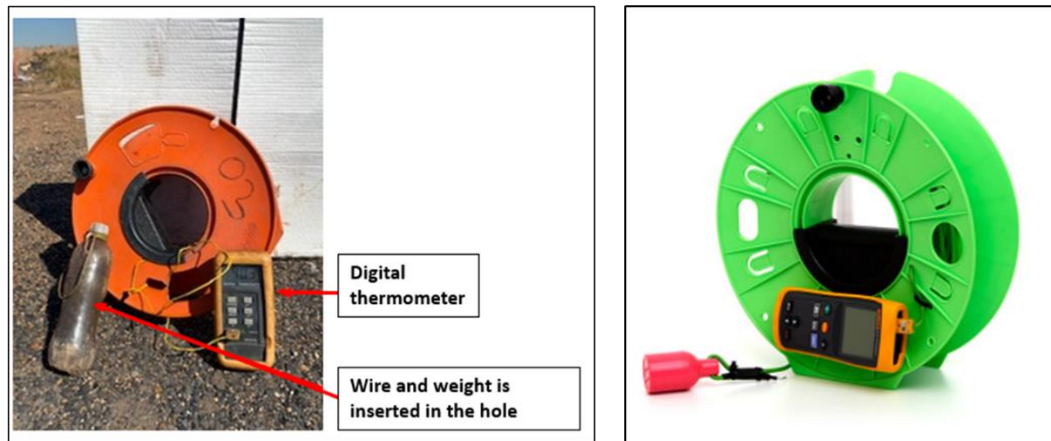


Figure 10: Examples of k-type thermocouple temperature measurement devices

An ideal temperature measurement device should have the following features for successful use in hot hole areas:

- Accuracy – the device should measure the in-hole rock surface temperature and/or the in-hole ambient air temperature accurately, relative to a standard calibrated instrument. Attention should be paid to factors that affect the accuracy of temperature readings such as:
 - The response time of the probe in giving a reading after immersion into a hole. Although devices vary, holding a device in place to avoid fluctuations for about 10 seconds should enable the detection of an accurate temperature reading.
 - The presence of water, dust, mud and smoke.
 - The failure to follow device set-up instructions.
 - The failure to calibrate the device correctly.
- Multi-point temperature detection – the ideal temperature measurement device should have multiple sensors along the length of the wire/cable/cord to enable the generation of a temperature profile of the hole. Alternatively, the device should capture the temperature of multiple points in the hole as it is inserted and pulled out of the hole to generate the temperature profile. It should not be assumed that the

temperature at the bottom of the hole would be the highest. Cracks along the hole from which heat may escape may lead to higher temperatures than the bottom of the hole.

- Length – the length of the wire/string/cable or any part of the instrument to be immersed into the hot hole should be adequate so that the entire depth of the hole is available for temperature detection.
- Durability – The in-hole wire/cable/cord should withstand wear and tear that may be caused by the rough and uneven in-hole conditions and ensure that the accuracy of measurements is not affected. Replacement parts should be readily available and easily installable on a mining block, without causing delays that may put workers at risk and reduce productivity.
- Set-up and measurement time – the time it takes to set up the device and its accessories before a temperature measurement can be made in a hot hole should be minimal. In addition, the time it takes to take a temperature reading should be preferably within 2 minutes after inserting the device into the hole. The set-up and temperature measurement time should not lead to any temperature measurement delays as time is of the essence on a hot hole block.
- Temperature range – the device should be able to measure the in-hole rock temperature and/or the in-hole ambient air temperature of up to 300°C. This figure is based on currently available devices with limited temperature ranges. Devices with higher limit temperature ranges would be ideal as some holes on a block may exceed 300°C.
- Visibility of temperature readings –temperature readings on the control system output (monitor, liquid crystal display (LCD) screen) should be visible in different environmental conditions such as direct sunlight, rain, darkness, or dust. Furthermore, the temperature readings digits should be distinctively clear to read and should not be confused with other (non-temperature) figures that may be displayed on the output device.

When using a temperature measurement device to detect the temperature of the hole, the instructions set out by the device manufacturer should be followed. The responsible legal appointee should ensure that the device is used correctly to measure the temperature of all the holes on a hot mining block. Furthermore, the correct temperature reading should be captured on plastic tags and placed at the crest of the hole. The readings should also be captured on the relevant data sheets and signed by the relevant authorities. Ideally, the capture of the temperature readings should be digital and

communicated to the relevant authorities in real or near real time for quick adaptations to risk mitigation measures. Other information about a hole that should be captured includes the hole depth and hole conditions such as the venting (and the colour), smoking (and the colour), presence of water and the smell released from the hole. All these factors would inform the risk assessment and the choice of risk mitigating measures.

Once the temperature readings have been taken and recorded. It is important to ensure that the holes are classified according to the mine-specific risk categories. Table 5 shows an example of how hot holes are classified at one of the opencast coal mines.

Table 5: Classification of hot holes based on temperature

Colour of Tag	Hole Temperature	Hole Type
White	<40°C	Cool Hole
Yellow	Between 40°C – 54°C	Hot Hole
Red	>55°C	Very Hot hole

c. Treatment of hot holes

Holes that have been identified and classified as “hot” (temperature of 40°C or more by regulatory definition), should be treated or managed according to the mine site risk assessment. This includes those holes that would have initially measured below 40°C but increased in temperature to a higher hot hole classification class between the time of drilling and the commencement of charging related activities. The treatment of hot holes aims to reduce the temperature of the hot holes to below 40°C, followed by applying risk mitigating measures relevant to normal holes. Failure to reduce the temperature of the hot holes to below 40°C means that the risk mitigating measures for hot holes should be applied. Risk mitigating measures used in the treatment of hot holes include the use of cooling agents (inadequate information available to make a recommendation), water (not recommended by mining and explosives personnel), foam expander plugs, gas bags, PVC sleeves, etc. Other risk mitigating measures include the sealing of the hot holes so that they are not charged. The review of the SOPs revealed that holes on a hot block may be sealed if they present hazards to workers on a mining block. The hazards may stem from venting, smoking or from temperatures above the upper threshold (for example, hot holes with a temperature greater than 100°C may be considered dangerous and require sealing). Breakthrough (bhoboza) holes may also be sealed off as they may facilitate the intake of oxygen which may lead to further increases

in temperature. The re-drilling of holes is also practiced by some coal mines. A new hole is drilled adjacent to a breakthrough hole (which eventually gets sealed). Drilling the new hole or the “re-drill” hole, for example, 2 m away and 2 m shorter than the initial hole, does not guarantee that it would be a solid hole in an undulating coal seam, nor does it guarantee that the temperature would be within the allowable temperature threshold. Therefore, mines should determine measures and specific details on re-drilling of holes when breakthrough holes are encountered. The mine risk assessments and SOPs should specify the exact temperature and conditions for which hot holes should be sealed. The following sections summarise the experimental findings and recommendations for the use of hot hole management tools.

Foam expander plugs

Foam expander plugs are used to seal off venting holes, holes with temperatures that pose a high risk to workers (holes with temperatures above the threshold) and breakthrough holes. Depending on the manufacturer, foam expander plugs may come as two chemicals, in two separate bags, that are mixed for expansion to commence. The plug is then inserted into a hole, after which it expands upwards and solidifies, thus, sealing off the hole as shown in Figure 11.



Figure 11: Foam expander plug on a hole collar

Engagements with mining personnel revealed that at high temperatures (approximately above 200°C) the solidified plug may catch heat and burn, realising some white smoke.

Therefore, the use of foam plugs to seal off hot holes at high temperatures should be investigated and incorporated into the risk assessment. The following practices are recommended when sealing off holes with foam expander plugs:

- Wearing of the correct personal protective equipment (PPE), particularly gloves and goggles.
- Ensuring that the foam plugs are stored safely away from direct sunlight as this may affect the effectiveness of the polyurethane mixture.
- Ensuring that an opening is created on the upper portion of the bag as an outlet for the foam expander plug.
- Recording information of all the sealed holes and communicating this with the relevant blast design or risk assessment authorities.

Gas bags

Gas bags are mostly used to seal off venting holes on a block. The gas bag tests conducted produced wide-ranging results. In some of the tests, the gas bags did not last in-hole for a period of 24 hours or longer in hot holes of temperatures greater than 43°C. Contradictory results were obtained for a different type of gas bag; the gas bag lasted for a duration longer than 24 hours. Based on these findings (although from a limited sample size), it is not advisable to seal off hot holes with gas bags over long periods as they may burst or deflate and enable the escape of smoke from within the hole. It is recommended that as part of risk assessment, tests on gas bags should be conducted on different sized holes of varying temperature to enable the identification of the optimal conditions for the use of gas bags to seal off hot holes.

PVC Sleeves

PVC sleeves are used as a form of physical separation between the surface of the hole and the hot hole specific emulsion. PVC sleeves could also function as a container for the emulsion in breakthrough holes, cracked holes, and pillar holes. It is noteworthy that the tests on PVC sleeves proved that the PVC sleeves provided some insulation by preventing the explosives product from gaining heat from the hot hole. The temperature difference between inside and outside the sleeve was maintained for a duration of up to 30 minutes, which was adequate for completing all required activities such as charging up, tying up, and the finalisation of preparing for the blast. Therefore, PVC sleeves are recommended for use in hot holes both as a container for the emulsion and as an insulating sheath. However, more tests need to be conducted to understand the varying

modes in which the PVC sleeves may fail after charging with emulsion thus, ensuring greater safety on the mining block.

d. Charging and blasting of hot holes

The charging and blasting of hot hole blocks are activities that rely heavily on time. The associated procedures for charging and blasting in hot hole areas are centered around working safely and promptly. The charging of hot holes can be categorised into two phases namely, before charging and during charging. Activities practiced before charging include selecting the type of explosives products and the relevant accessories, measuring the temperature of the hole before charging commences, delineating the block, readying the mobile mixing units (MMUs), preparing the hot hole management tools to be used, and identifying the key personnel to perform the charging activities. Activities conducted during charging on hot hole blocks include monitoring the temperature of emulsion, following a specific loading sequence, and continuously assessing the block for any hazards.

Selecting explosives products and accessories

The selection of explosives products and accessories for use in hot hole environments should be informed by the mine site conditions (Figure 8) and the associated risk assessments. Additionally, large scale tests on the explosives products should be conducted at the mining sites. These tests assist decision makers in identifying the full spectrum of the risk associated with blasting in such environments by utilising the actual conditions (hole depth, hole diameter, in-hole temperature etc.). When the products have been selected, the mine site risk assessments, which would have classified the risk associated with the hot holes according to in-hole temperatures should be followed in conjunction with the relevant technical data sheets from the manufacturer. Blasting accessories such as initiating systems used in hot hole environments should be compatible with the selected hot hole specific explosive product.

Congestion on the block

Interactions between people and machines on a hot hole block should be minimised. Only those workers who are deemed necessary to be on the block during charging should be present to avoid congestion and disorder during an event.

Bulk explosive equipment

The number of bulk explosives trucks used to charge a hot hole block should be compatible with the number of holes to be charged to reduce any delays that may be of high risk to workers on the block. Back-up (standby) trucks should be available in case of breakdowns.

Loading sequence

There are various ways in which the hot holes on a block can be loaded. The choice of loading sequence should be informed by the overall risk associated with the hot hole block. The aim should be to load the hot holes as quickly as possible in a safe manner, allowing for an escape route for workers to get out of the block. The following loading sequences were identified:

- Loading in the sequence in which the blast will be fired to allow the pattern to be quickly tied up and fired in the event of a change in site conditions like the weather (AEISG, 2020).
- Loading the hottest holes last – may lead to cross charging but reduces the risk of an increase in the temperature of the emulsion while workers are in the vicinity.
- Loading the hottest holes first – this sequence was found to be disadvantageous in that it leads to cross charging on a block, which may create movement inflexibilities and may lead to the workers getting stuck on one corner of a block.
- Loading from the farthest hole first and progressing towards the block entrance to allow for an escape route in case of an emergency.

Monitoring the temperature of the explosive product (hot hole emulsion)

Temperature monitoring devices are used to monitor the temperature of the emulsion after the holes have been charged. Since charged hot holes are associated with unexpected detonations, this is a critical stage in maintaining the safety of workers, equipment, and infrastructure. The workers and in particular, the legal appointee responsible for the block should ensure that monitoring devices are placed in all the hot holes. Furthermore, the workers should be aware of the warning alerts (alarm or LEDs) and the risk mitigating measures associated with them. For example, if the temperature monitoring device detects an increase in the temperature of the emulsion to that above the threshold limits, (e.g., above 80°C), workers should know what risk mitigating measure to implement timeously and safely. The ideal device to be used for monitoring

the temperature of hot hole emulsion should have similar characteristics as those for a temperature measurement device (Section 3b). In addition, the device should have the following features:

- Response time – the device should detect the slightest change in the temperature of the hot hole emulsion and signal an alert (sound or warning light) if a threshold limit is exceeded to afford workers the time to evacuate a block if it is deemed necessary to do so.
- Visibility of warning lights – the warning lights should be visible from all directions on the block in different conditions such as dust, rain, fog, and direct sunlight.
- Audibility of warning alarm – the alarm should be audible throughout the block, even in the presence of explosives trucks and other equipment.

General charging good practices

The following practices are recommended for charging and blasting in hot hole environments:

- Detonators should not be used for priming because they trigger at temperatures between 80°C and 110°C.
- Top priming should be implemented.
- Hot hole specific emulsion-based explosives should be used (instead of ANFO) because of their better tolerance for heat as they contain up to 20 % water.
- Hot holes should not be stemmed because this may promote the premature detonation of the explosive due to heating under confined conditions.
- The sleepover of charged holes should be avoided as this may result in unexpected spontaneous explosions due to in-hole temperature increases.

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Appendix A (Milestone 2: Review of hot hole temperature measuring and monitoring instruments)

Executive summary

The main objective of the project is to develop guidelines to be used in the management of hot holes in South African surface coal mines. Hot holes are defined as those shot holes, in a coal mine, which after being drilled have an in-hole ambient temperature of 40°C or above, or show a temperature increase of 3°C or more during monitoring. Working in such environments poses a risk to workers on the bench. In particular, the charging of explosives in these holes may lead to the premature detonation of explosives or accessories, which may cause harm to people and damage equipment and mine infrastructure. Additionally, the high temperatures may reduce the effectiveness of the explosives products, causing suboptimal blasts. It is therefore important that mines adopt comprehensive hot hole management practices to reduce these risks.

The current milestone (Milestone 2: Review of temperature monitoring devices for hot hole management) aims to review local and international temperature monitoring devices that are suitable for application in hot hole environments in surface coal mines. The use of temperature monitoring devices is in line with the Department of Mineral Resources and Energy (DMRE) regulations which stipulates that mines should continuously monitor a hole throughout its length from when it is drilled until it is charged.

Different types of temperature measurement and monitoring devices were investigated. These include a variety of thermometers, thermocouples and non-contact devices. These devices have wide applications that include nuclear and other power generation plants, the automotive industry, in metal alloy production and to a less extent in the mining industry. Thermocouples and non-contact devices such as infrared were identified as having properties suitable for use in hot hole environments. These devices would however need to be adapted to the harsh hot hole conditions which often contain debris, water, smoke and dust.

The review of temperature monitoring devices revealed that there are a few companies that specifically manufacture hot hole monitoring devices for use in the mining industry both locally and internationally. Some devices found are in the early development stages and thus contain inadequate specifications data. In some cases, manufacturers of temperature devices used in other industries showed a willingness to customise their products for use in measuring the temperature of hot holes in surface coal mines.

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1. Introduction

Open cast coal mining is employed in areas where the coal seam is close to the surface and allows for the recovery of larger coal deposits compared to those of underground coal mining (Ramane, 2014). In open cast mines, overburden is removed to expose the coal seam that is then drilled, blasted, and hauled for economic purposes (Chaulya & Prasad, 2016). In some coal mining operations in South Africa, surface coal mining occurs above old underground workings.

Mining above old underground workings comes with its own challenges such as drilling into hot and or burning areas and the drilling of run-away holes (holes drilled into old underground openings or non-solid ground). Such holes are then exposed to spontaneous combustion, which occurs because of the oxidation of coal (Sloss, 2015). When air seeps through cracks formed by fracturing and porosity, and encounters coal, oxidation occurs. Oxidation is an exothermic reaction, where heat is released and since the heat is trapped in underground workings, it leads to a constant increase in the temperature of the rock mass and that of the drill hole air. Loading of explosives under such high temperatures is a dangerous process that can cause premature detonation or failure of explosives and initiating systems. This may lead to injuries and fatalities on the block and in the vicinity of the area (Anthony & Grobelaar, n.d.). Hot holes are defined as *“shot holes, in a coal mine, which after being drilled have an in-hole ambient temperature of 40 °C or above, or an increase of 3°C or more”* (Mine Health and Safety Council, 2019). The Mine Health and Safety Act's explosives regulations stipulates that a mine should draw up a procedure to prevent workers from the risk of hot holes. The procedure should include the monitoring of the temperature of a drill hole (throughout its length) after it has been drilled until charging up (Department of Mineral Resources, 2015).

The varying mining conditions lead to different mines adopting standard operating procedures specific to their conditions. For example, according to Matrix (2021) holes with temperatures between 40°C and 60°C, can be primed and charged as per the hot hole procedure. In hot holes where temperatures exceed 60°C, cooling agents and water are used to cool the hole down and reduce temperatures before charging however, if temperatures do not decrease, the hole is sealed and not charged (Matrix, 2021).

It is difficult to determine whether a drill hole is hot or not by just observing it from surface. There are indicators such as venting or smoking of the holes that are sometimes used to identify a hot hole. However, the indicators obtained from this technique do not provide adequate information such as the exact temperature of the holes, allowing the implementation of appropriate control strategies to prevent the risk of accidental detonation of explosives. Therefore, temperature measurement and monitoring instruments are used by mines to assess hole temperatures from the time of drilling to just before blasting as per the regulations. Temperature measurement devices detect the temperature and display the output on a type of a monitor or screen. They are generally used to take readings from the time a hole is drilled until charging. These devices are of different types, and they vary according to the method they are designed to use in detecting the temperature. The methods of detection include:

- In-hole air temperature measurement.
- In-hole rock surface temperature measurement.
- Non-in-hole/surface temperature measurement devices.

Temperature monitoring devices are disposable devices designed for use during charging, to monitor the temperature change of hot hole emulsion (Australasian Explosives Industry Safety Group (AEISG) Inc, 2021). They are implemented as a safety measure to enable the early detection of the risk of premature detonation due to the increase of explosives temperature. If the temperature monitoring device detects an increase of temperature to that above the set safe-to-work temperature cut-off (e.g., 55°C), workers are immediately evacuated from the mining block. It should be noted that some devices have the functionality to be used for both temperature measurement before charging and the monitoring of the hot hole emulsion temperature during charging.

The different temperature measurement and monitoring instruments include thermocouples, infrared guns and infrared cameras. The instruments have varying limitations that include inaccurate temperature readings due to the presence of water, smoke or dust, the requirement for intensive labour and lack of functionality to detect the temperature throughout the depth of a hole. It is important for mines to select an appropriate device that suits the site conditions and provides accurate results that may be used to reduce the risk associated with hot holes. Additionally, the use of the device should not impede on productivity on the bench.

This report gives a summary of local and international temperature measurement and monitoring devices that may be used for the management of the risk associated with hot holes. In addition to this report, tests were conducted on four types of temperature measurement devices and two types of temperature monitoring devices and the results form part of Milestone 3 (Standard operating procedures (SOP) reviews, on-block observations and experimentation at test site) report.

2. Temperature measurement and monitoring

Temperature measurement and monitoring is applied in several industries that include nuclear power generation, the aerodynamic industry (for rocket exhaust gases), manufacturing and processing industries and mining. In these and other applications, the measurement and monitoring of temperature is important for safety of people and the environment and for the efficient functioning of processes, equipment, and technologies over periods of time (Satyendra, 2020; Missouri S&T, 2021).

A variety of instruments are used for temperature measurements and these instruments vary according to the accuracy of measurement, size, method of detection (invasive or non-invasive), range of operating temperatures and other parameters. The hot hole environment in mining operations similarly requires temperature measurement and monitoring instruments tailored for the specific conditions that usually have water, smoke, mud, and debris.

Temperature measurement instruments can be classified into thermometers, probes, and non-contact devices (Missouri S&T, 2021). The different types of thermometers include mechanical, indicator, resistance, optical and radiation thermometers as shown in Table 6 (ABB, 2013; Satyendra, 2020). The temperature range of a thermometer and the accuracy of the temperature readings depends on the size of the hole, the length of the tube and the fluid in the thermometer (Missouri S&T, 2021). More specifically, the accuracy of a

reading is affected by the pressure exerted on the thermometer bulb. No evidence of the use of thermometers for hot hole mining environments was found. It is however implied that these devices may be unsuitable for the harsh hot hole environment due to their delicate nature. Thermocouples are a type of measuring device used in the mining industry. A thermocouple is an example of a simple temperature measuring instrument that is used to measure the in-hole air temperature. It is connected to a digital thermometer where temperature readings are taken as the thermocouple is inserted down the hole. The thermocouple measures the temperature at one position in a hole (bottom of a hole or at a given depth of the hole), rather than producing a full temperature profile of the hole. Other temperature measuring instruments include various types of infrared devices such as infrared guns and in-hole infrared temperature measurement instruments. Infrared guns, although they are easy to use, are limited by environmental factors such as the presence of water and dust in holes and their effectiveness is limited to short holes of approximately 5 m (Australasian Explosives Industry Safety Group (AEISG) Inc, 2021). In contrast, in-hole infrared temperature measurement devices are suitable for deep holes due to the flexibility to choose variable cable lengths but, according to the AEISG (2021), these instruments are labour intensive, requiring a minimum of two people to operate.

Table 6: Major types of temperature measurement devices (ABB, 2013; Satyendra, 2020)

MEASUREMENT METHODS	MEASUREMENT TYPES	TEMPERATURE RANGES (°C)	ERROR LIMITS
Mechanical thermometers	Non wetting liquid filled glass thermometer	-38 to 630	As per mechanical thermometer standards
	Wetting liquid filled glass thermometer	-200 to 210	As per mechanical thermometer standards
Indicator thermometers	Bimetal thermometer	-50 to 400	1 – 3% of indicator range
	Liquid filled spring thermometer	-30 to 500	1 -2% of indicator range
	Vapour pressure spring thermometer	-200 to 700	1 -2% of scale length
Resistance thermometers with metal resistors	Pt-resistance thermometer	-200 to 1000	Temperature dependent (0.3 to 4.6°C)
	Ni-resistance thermometer	-60 to 250	Temperature dependent (0.4 to 2.1°C)
Radiation thermometers	Infrared radiation pyrometer	-100 to 2000	In the range of -100 to 400 (0.5 to 2°C) or 0.5 to 1.5 % of the temperature
	Thermography instrument	-50 to 1500	
	Quartz thermometer	-80 to 250	Resolution 0°C
	Gas thermometer	-268 to 1130	Design dependant
	Thermal noise thermometer	-269 to 970	0.1%
Semiconductor resistance thermometers	Silicon measurement resistor	-70 to 175	0.2 to 3°C

	Hot wire resistance thermometer, thermistor	-40 to 180; -60 to 200 and -100 to 400	Temperature dependant (0.1 to 1°C and 0.5 to 2.5 °C)
Optical methods	Fibre optic luminescence thermometer	Max 400	0.5°C

Probes, unlike thermometers which rely on a liquid or gas, use different thermocouple material for temperature measurement. Temperature probes are categorised into resistance elements, thermopiles (or thermocouples) and semiconductors (Missouri S&T, 2021). Resistance element examples include thermistors (a thermal resistance element that changes its resistance with temperature) and resistance temperature detectors (RTDs) based on the changes of resistance in pure metals. According to Missouri S&T (2021), thermistors have good accuracies of between 0.1°C and 0.2°C and temperature ranges of between 0°C and 100°C. These devices are small and are less costly than resistance temperature detectors. The accuracy of thermistors is however affected by their self-heating nature (Satyendra, 2020). Thermistors are normally encapsulated in different materials (Figure 12) to form a temperature probe and are suitable for lab uses rather than industrial applications (Satyendra, 2020; Missouri S&T, 2021).



Figure 12. Examples of thermistor-based temperature probes (Missouri S&T, 2021)

RTDs often consist of a length of platinum (and to a lesser extent, copper, tungsten and nickel) wire wrapped around a ceramic or glass core to protect the fragile element. The temperature range for platinum RTD probes is -270°C to 850°C. The accuracy of these devices is affected by their self-heating nature; however, they are still more accurate than thermistor-based probes (Satyendra, 2020; Missouri S&T, 2021). RTD probes are commonly used to sense the winding temperature of motors, generators, and turbines (Satyendra, 2020).

Thermocouples connected in series are called thermopiles and are used in the measurement of thermal radiation. The thermocouple, on its own, is a commonly used device in many industrial applications as a single junction device (Missouri S&T, 2021). A thermocouple is made up of two dissimilar wires, welded or physically joined together (ABB, 2013; Missouri S&T, 2021). The various types of thermocouples include the base metal thermocouples J, T, K, N and E and precious metal thermocouples S, R and B (Pearce, et al., 2012; ABB, 2013). These thermocouples and the corresponding properties, including the colour codes used, are shown in Table 7.

Table 7. Various types of thermocouples and properties, adapted from Missouri S&T (2021)

Type	Materials	Min Temp (°C)	Max Temp (°C)	Colour	Outer Cover
J	Iron	0	750	White	Black
	Constantan (Cu-Ni)			Red	
T	Copper	-250	350	Blue	Blue
	Constantan (Cu-Ni)			Red	
K	Cromel (Ni-Cr)	-200	1250	Yellow	Yellow
	Alumel (Ni-Al)			Red	
E	Cromel (Ni-Cr)	-200	900	Purple	Purple
	Constantan (Cu-Ni)			Red	
N	Nicrosil (Ni-Cr-Si)	-260	1300	Orange	Orange
	NiSil (Ni-Si-Mg)			Red	
S	Platinum-13% Rhodium	-50	1768	Black	Green
	Platinum			Red	
B	Platinum-30% Rhodium	0	1820	Grey	Grey
	Platinum-6%Rhodium			Red	
C	Tungsten-5% Rhenium	0	2320	White	White/Red Stripe
	Tungsten-26% Rhenium			Red	

Type J and K thermocouples are the most used in industrial applications. Pt-Rh sensors are employed in the majority of power and process applications, such as power generation plants, aerospace heat-treatment plants and gas turbines up to about 1600°C (Pearce, et al., 2012). To achieve accurate temperature readings, thermocouples and thermocouple wires are often insulated with materials such as glass fibres, mineral fibres, polyvinyl chloride (PVC), silicone rubber ceramic, perfluoroalkoxy (PFA) or magnesium oxide and aluminium oxide (ABB, 2013).

Another group of temperature measuring instruments is the non-contact devices, which are based on the radiation emitted by objects. Although these devices were used in environments that exceed 700°C, adaptations have been made to allow for the measurement of lower temperature ranges. Some of the applications for non-contact devices such as infrared pyrometers are (ABB, 2013):

- Automotive industry.
- Chemical industry.
- Cement and lime furnaces.
- Metal and alloy production.
- Textile industry.
- Fire chamber measurements in power plants and waste incineration.

In addition to their non-contact properties, other advantages of infrared devices include fast response time, improved accuracy in comparison to thermocouples and the provision for remote temperature read-outs (ABB, 2013; Williamson, 2018). Infrared devices are however more costly than thermocouples, the accuracy of temperature measurements may be affected by optical obstructions and reflective materials (Williamson, 2018).

3. Temperature measurement and monitoring devices for hot hole management

The type of a device selected for measurement and monitoring of hot hole temperature will vary from mine to mine due to the different mining conditions, mining designs, and risk assessment and management procedures. In addition to these factors, the selection process should be guided by the factors discussed in the following sections.

The stage at which device is used (pre-charging or during charging)

The stage, during the drill and blast cycle, at which a device is used is important in selecting the correct type of device. There are available devices for use pre-charging and during charging. Devices used pre-charging are temperature measuring devices such as thermocouples and infrared instruments. These devices are used to measure the temperature of either the in-hole rock surface or the in-hole air temperature from the moment a hole is drilled until prior to charging. In contrast, temperature monitoring devices are used to monitor the temperature change of explosives products such as hot hole emulsion during charging until prior to the setting-off of a blast. These devices are blasted with the rock and thus are part of consumables in the blasting process. Such devices normally use an indicator (audio, or colour change) to alert workers of an increase of explosives temperature to levels above the set cut-off temperatures, following which risk management measures such as the immediate evacuation of workers from the block are implemented.

The method used to detect the temperature (in-hole or from surface)

Temperature measurements are conducted either from within the hole or from surface. The selection of a device should be guided by the level of accuracy needed from the temperature readings for the relevant risk management process. According to the AEISG (2021), it is advisable to use in-hole temperature measurement and monitoring devices as they have the ability to produce a temperature profile throughout the depth of the hole. In comparison, devices that measure or monitor the temperature from the surface, such as infrared guns, should be supplemented by measurements from other more accurate devices. This is because infrared guns are limited by the hole length and the associated spot ratios (Australasian Explosives Industry Safety Group (AEISG) Inc, 2021).

Heat source measured (rock surface or air temperature)

There are different types of in-hole temperature measurement and monitoring devices that measure either the in-hole surface temperature or the in-hole air temperature. In-hole infrared temperature probes are an example of devices used to measure the temperature of the in-hole rock surface, whereas thermocouples are used to measure the in-hole air temperature.

To this end, a literature review was conducted to identify available temperature measurement and monitoring devices that could be used for hot hole management in surface coal mines. This section gives a summary of international and local devices that could be used for measuring/monitoring temperatures of hot holes in surface coal mining environments.

3.1 Local temperature measurement devices

Based on the literature review conducted, there are few temperature measurement devices manufactured locally. Several companies that manufacture such instruments were contacted; however, few hot hole suitable instruments were found.

3.1.1 PTM-806 Model Thermocouple

The PTM-806 Model Thermocouple is a device developed by Test and Measurement Instruments C.C. (TMI). According to Griesel (2021), the device is not designed to function in hot holes however it can be modified for hot hole applications (Figure 13). It comes with a special probe that measures temperatures to a maximum of 1200°C. It comes with a standard 2 pin type K input socket, has two type display (normal and reverse), is battery powered (4 PCs and DC 1.5V) and weighs 156g (Griesel, 2021). It has an auto power-off installed which saves battery life. The built-in microprocessor circuit ensures high accuracy with a sampling time of approximately 1 second (Griesel, 2021). At the time of the compilation of this report, the manufacturer had not yet responded to the requests of the researchers for more information and the cost of the thermocouple. This device is thus, applicable for in-hole air temperature measurements pre-charging.



Figure 13: PTM-806 Model thermocouple (Griesel, 2021)

3.1.2 Thermo-Hygrometer

The Thermo-Hygrometer is a handheld device developed by BAMR (Figure 14), a company that develops a range of measuring instruments. Contact was made with one of the representatives to enquire about the device. According to Dennise (2021), the device is battery powered (9V) and measures temperatures accurately at a fast rate even in humid environments. The humidity and temperature sensors on it are replaceable. It features an infrared, non-contact surface IR temperature probe. It is able to store approximately 8000

results including date and time through a push of a button on the device. Temperatures at a range of -20 to 80°C with an accuracy of +/-2°C can be measured. The Thermo-Hygrometer is generally used in concentration to measure moisture content, however, it may also be used to measure temperatures in hot holes (Dennise, 2021). Temperature measurements can be taken by pointing the device in the hole, focusing the laser on the desired area, and pressing the “measure” button on the device. Its advantages are that its portable, allows the operator to measure rock temperature and store the data. The cost of the device is R11 000.00 (excluding VAT).



Figure 14: Hand-held Thermo-Hygrometer (*Laboratory Equipment Supplies, 2021*)

In summary, this device is suitable for applications prior to charging to measure the in-hole rock surface temperature. The device is limited in that some hotspots in a hot hole may be omitted due to the lack of in-hole temperature measurement capabilities.

3.1.3 Hot hole Management System (HHMS)

The HHMS, a product developed by PositionXT, is a tool for surveying the temperature profile of a hole in order to identify whether the hole is categorised as hot or not (PositionXT, 2021). The tool is designed to monitor temperatures during charging the holes with explosives. The tool consists of a Hot Hole Display Node (HHDN) and a Hot Hole Alarm Node (HHAN) which are connected to a hot hole temperature wire interchangeably as shown in Figure 15. Sensors, at specific intervals, are installed on the temperature wire to detect the temperature in the hole. The information is relayed to the HHDN to produce a temperature profile along the depth of the hole. According to PositionXT (2021), the number of sensors on the temperature wire can be tailor-made for specific mine conditions and preferences.

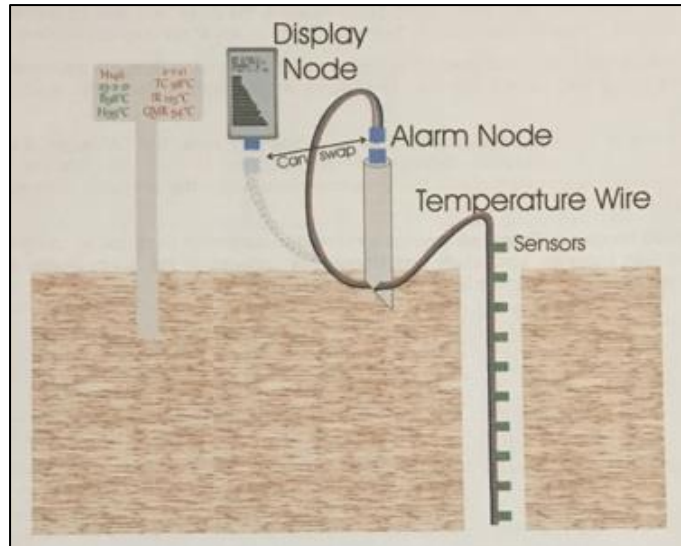


Figure 15: The Hot Hole Management System accessories (*PositioNXT, 2021*)

The HHAN, Figure 16, uses a combination of sound (alarm buzzer) and sight (LED flashes) to alert workers on a mining bench about the temperature changes in a hole. The alarm node sounds a constant tone for temperatures from 90°C to 128°C (maximum temperature) however, it can be set to customer requirements to sound an alarm from a minimum of 50°C to a maximum of 128°C. The LED flashes provide a visual alert at different temperature intervals summarised below:

- Green flash – temperatures below 50°C.
- Magenta (pinkish red) flash – temperatures between 50°C and 89°C.
- Cyan (light blue) – temperatures between 90°C and 128°C.

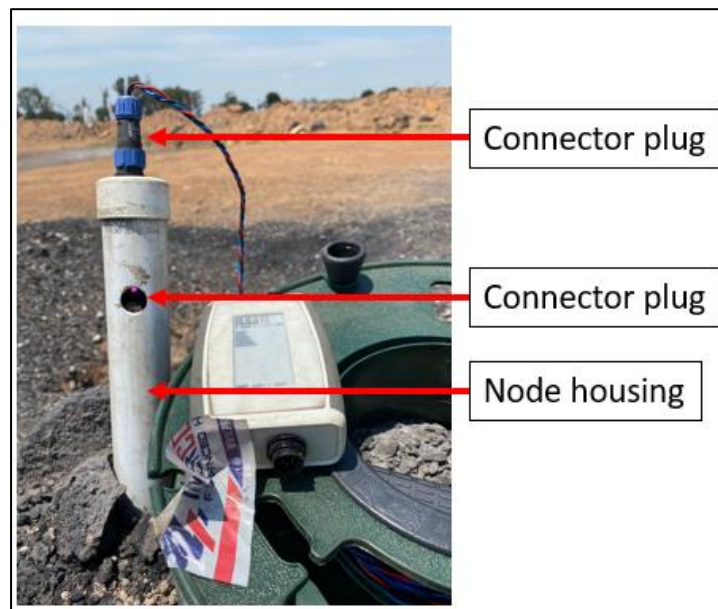


Figure 16. The Hot Hole Alarm Node (*Position NXT, 2021*)

The HHAN can be plugged to the temperature wire using a similar connector to that used for the alarm node. The device uses an “ePaper” screen, depicted in Figure 17, which enables the readings to be visible under direct sunlight, however, it requires external lighting in the dark. The HHAN displays the following information on the screen:

- The minimum and maximum temperature in the hole.

- The sensor numbers corresponding to the minimum and maximum temperatures.
- The number of sensors detected on start-up.
- The temperature range (0°C to 128°C).
- The temperature profile of the hole in the form of black horizontal lines, where each line corresponds to the temperature detected by a specific sensor.

The OEM was contacted regarding the cost of the product however, this information was not disclosed. Furthermore, according to the OEM, a new improved model of the device is currently under production.

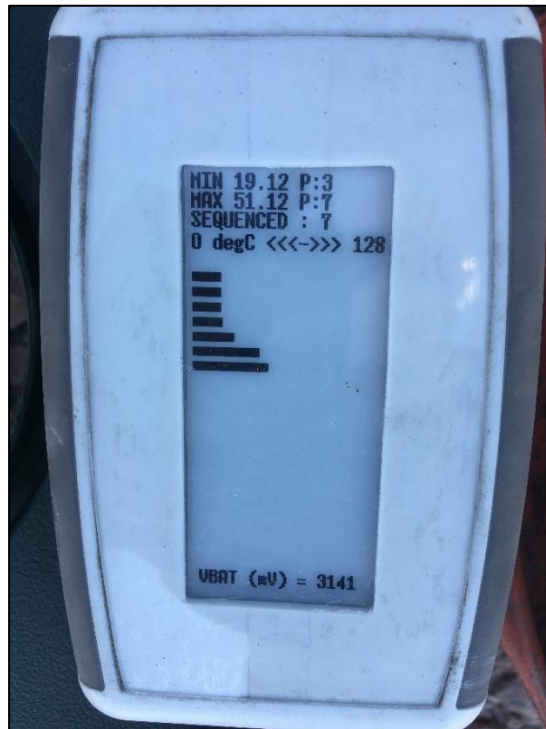


Figure 17: The Hot Hole Display Node

In conclusion, based on the currently available information, this device is suitable for both in-hole air temperature measurement, pre-charging and for the in-hole temperature monitoring of hot hole emulsion during charging. The device was tested and the results that include the temperature measurement duration are included in the Milestone 3 (SOP reviews, on-block observations and experimentation at the test) report.

3.1.4 UNI-T Handheld Infrared Thermometer

The UNI-T handheld infrared thermometer is manufactured by CIB Partners which sells various machinery and equipment such as saws, drills and jointers. This handheld device can be used to measure in-hole temperatures (Figure 18). It is a lightweight (0.27 kg) non-contact instrument that functions in distance to spot ratios of 12:1, measures temperatures ranging from -18°C to 350°C and has a quick response time of 250 ms (CIB Partners, 2020). It is operated by pointing the laser to the object of interest. The unit is powered by a 9 V battery and costs R1 545.60. The advantage of using it is that it measures the hole's rock temperature instead of ambient temperature, however, it may result in errors when used to measure temperatures in deep holes, venting holes, holes with dust. According to AEISG (2021), infrared devices are used optimally for shallow depth holes of about 5 m. When compared to a traditional thermocouple that can be destroyed by high temperatures

in a hole, the UNI-T thermometer is not physically exposed to the hole's temperature and therefore can be re-used several times, making it last a long time.



Figure 18: UNI-T handheld infrared thermometer (CIB Partners, 2020)

This device is used for applications such as during pre-charging, to measure the in-hole rock surface temperature. The device is used from the surface and pointed into the hole, therefore, some positions in the hole may not be measured thus leading to the omission of hot spots.

3.1.5 Ningi Safeblast

QuickBlast is a measuring device manufactured by Ningi Services. It measures the depth and ambient air temperature in a blast hole as per the prescribed depth range by customers (Figure 19). It can take multi-point temperature readings along a hole. The device constitutes of an LED display pod and a weighted cable which is reeled down to the bottom of the blast hole (Ningi Services, 2021). The weighted cable length varies based on customer specifications. The display pod has 10 LED windows that represent different depth ranges. The 10 LED windows are linked to 10 air sensors that are embedded on the weight cable. The sensors are equally spaced as depth range requested by the customer. According to Ningi Services (2021), light indicators are shown on the 10 LED windows and the first indicator to appear will be for the first sensor (on the weighted cable) at the bottom of the blast hole. The light indicators have different colours (as shown in Figure 15) which represent different temperature ranges. The green light represents temperature ranges 0°C -79°C, orange light 80°C -99°C and red light represent $\geq 100^{\circ}\text{C}$. When measuring temperature in a hole, the device is used as follows (Ningi Services, 2021):

- The user will reel the cable down to the bottom of the blast hole. The LED light indicators will show on the display pod according to the prescribed temperature range.
- An early warning alarm with ascending volume will sound in the event of escalating temperature readings.
- Only the cable is inserted in the hole, the LED display pod is left outside the blast hole for ongoing temperature monitoring. Prior to blasting, the LED pod is disconnected.

- The cable may be left in the blast hole during charging and detonated during the blast event.
- The LED pod is Bluetooth enabled to upload field data to a Ningi QuickBlastApp which is accessed from any smart phone or tablet.

The advantage of this device is that the user can get the temperature profile of a blast hole which assists in understanding the temperature variation in a hole.

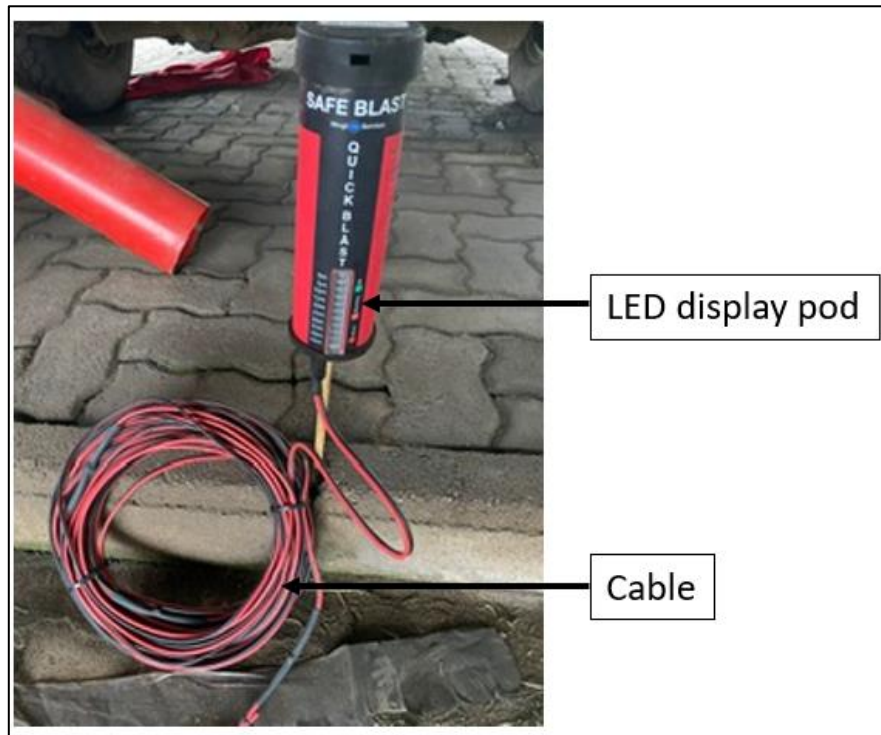


Figure 19: QuickBlast depth and temperature measuring device (Ningi Services, 2021)

This device can be used during charging stage of the drill and blast cycle for measuring the in-hole air temperature and for monitoring the temperature of explosives. The weighted cable is the disposable part of the device. The cost of the device is available on the customer's request.

3.1.6 Ningi infrared profiler probe

IR profile probe is a measuring device manufactured by Ningi Services (Figure 20). It uses 360° infrared temperature sensors that measure the blast hole circumference. It has a handheld controller device which displays multi-point temperature reading across the blast hole circumference at a specific depth level. It has the functionality of an early warning alarm when escalating temperature readings are encountered. It has operating temperature range from -40°C to 125 °C (Ningi Services, 2021). At the time of reporting, it was a concept device where the prototype was tested at an open cast coal mine. According to the coal mine representative, the test results were unsuccessful. The device is undergoing further developments and not yet available for purchase.



Figure 20: Ningi infrared profiler probe (Ningi Services, 2021)

3.1.7 Designs Unique Multipoint Blast eye Mk2

This device is manufactured by Designs Unique, which also manufactured the original Blast eye from AEL. The device is an advanced version of the original Blast eye device. It measures the ambient air temperature in a blast hole as per the customers specifications. The research team tested the prototype version of the device (during Milestone 3), but the manufacturer has made significant improvements to the device which is currently used in production at a coal surface operation in South Africa.

The Multipoint Blast eye is used to monitor hole temperatures during charging (particularly hot hole emulsion temperature). It constitutes a reel/cable and a receiver unit (Figure 21). The cable has sensors spaced out at 5m apart which allow the user to measure multiple temperatures along the hole depth and it is 40m long. The receiver unit has a several small windows that display colour coded LED light indicators which represent different temperature ranges. A green light indicates that the temperature is ok, an orange light indicates that the hole should be monitored carefully, and a red light indicates that the temperature is critical. The receiver unit also sounds a single alarm at 80 °C and a continuous alarm at 100 °C. The receiver unit uses disposable batteries that last approximately 8 hours with a sounding alarm and approximately 70 hours without a sounding alarm. The advantage of the device is that it allows the user to identify and monitor hot spots along the hole. The cost of the device will depend on the specifications of the customer such as the number and sensor spacing along the length of the cable.



Figure 21: Multipoint Blast eye

3.1.8 Kimo TT21

The Kimo TT21 is a device that is manufactured in France. It is a thermometer that is used when measuring in hole ambient temperatures pre-charging and during charging. The thermometer displays the temperature readings in Degrees Celsius and Fahrenheit therefore the user needs to constantly check that they are measuring using the correct unit. It is battery powered, compact and portable, making it easy to carry in the field (Stenzel, 2021). A single device costs about R 3 000.00 (excluding VAT) (Figure 22).

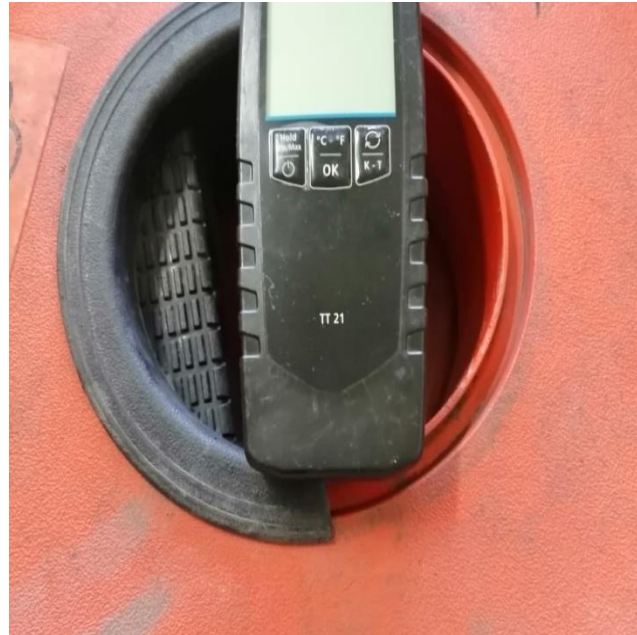


Figure 22: Kimo TT21 device (Stenzel, 2021)

3.1.9 Sinometer DM6801B

The Sinometer DM6801B is a K-type device that is manufactured in China (Figure 23). It is commonly used in various coal mines in the Witbank area. The thermometer can be used when taking temperature measurements pre-charging and during charging. It displays the temperature measured at a particular point along a hole. The thermometer displays the temperature readings in Degrees Celsius and Fahrenheit therefore the user needs to constantly check that they are measuring using the correct unit. It costs approximately R3 000.00 (excluding VAT).

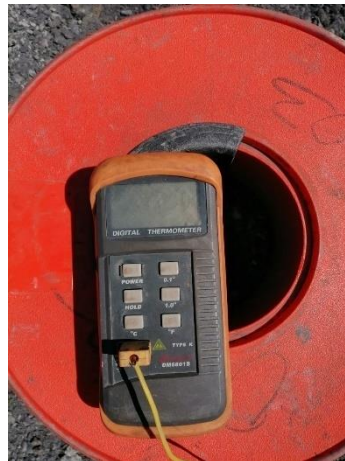


Figure 23: Sinometer DM6801B (Stenzel, 2021)

3.1.10 Fluke K-type unit

The Fluke is a temperature measuring device that is supplied by Electro Field Services but manufactured by Fluke Corporation. It constitutes a k-type thermocouple wire that can be connected to a multimeter (Figure 24). It is used to measure in hole ambient air temperatures pre-charging and during charging up to a maximum of 127°C. The wire is rolled up and encased in a metal sleeve and the multimeter shows the measured

temperature. Some of the disadvantages about the device is the reels that can get heavy during usage and the metal sleeve that may indicate inaccurate temperature readings because it requires time to heat up when taking temperature measurements (Stenzel, 2021). The device costs R12 140. 00 (excluding VAT).



Figure 24: Fluke K-type unit (Stenzel, 2021)

3.2 Local temperature monitoring devices

3.2.1. Hot hole Monitor (Blast Eye)

The Hot hole Monitor, also called the Blast Eye, is a device developed by AEL. It is a handheld temperature device that can be used to monitor temperature changes in hot holes and provides early warning for changes in blasting conditions (Figure 25) (AEL, 2018). It has a 30 m temperature probe wire that is dropped down the hole. If the temperature of a hole is between 55°C and 80°C, the device will sound a pulsing alarm and the LED on the side will start flashing. If the temperature of a hole is above 80°C, the device will sound a continuous alarm and the LED on the side will remain ON continuously. One unit costs R 642 (Communication with a mine representative where the unit is being used to measure hole temperatures). This second alarm indicates that it is not safe to carry out activities in the vicinity of that hole and therefore operators should evacuate the block. The main disadvantage of the device is that it monitors the temperature change at one point along the depth of the hole. In this way, hot spots in other locations of the hole, that may lead to an increase in the temperature of the emulsion may not be detected resulting in premature detonation of explosives. Additionally, through the use of the device, the early detection of an increase in the temperature of the emulsion is missed until the cut-off temperature is reached, leaving little time for workers to implement appropriate risk management procedures.



Figure 25: Hot hole Monitor (Blast Eye) (AEL, 2018)

The Hot Hole Monitor was tested, and the qualitative results are included in the Milestone 3 (SOP reviews, on-block observations and experimentation at the test) report.

3.3 International temperature measurement devices

3.3.1 Thermometer blast hole temperature probe

The thermometer blast hole temperature probe is a device that has been developed by an Australian based manufacturer called MTI Group (Figure 26). The company has recently set up a business development office in Middelburg South Africa. The company manufactures a range of modular drills and blast products for both underground and surface mining operations.

According to MTI Group (2021), the Thermometer blast hole temperature probe is durable and affordable as compared to other geotechnical instrumentation. It consists of the K-type thermocouple that is 30 m long and has 0.5 m graduation markings. It is mostly used to measure borehole temperature and can measure minimum temperatures of -50°C and temperatures of up to 150°C .

The device comes with a hot hole dipping tape that can be used for quality assurance (QA) checks on blast holes before charging. It can be used to measure temperature in hot holes. The device comes with a handheld unit, cable and the reel and costs around R4 800.00 (Kgarume, T. (2021), Email to JJ Duvenhage, October 21).



Figure 26: Thermometer blast hole temperature probe (MTI Group, 2021)

This device is applicable for measuring the in-hole air temperature from the time a hole is drilled until before charging commences. Depending on the costs of disposing of the thermocouple wire, such a device can be used during charging to monitor the temperature change of emulsion (Australasian Explosives Industry Safety Group (AEISG) Inc, 2021).

3.3.2 Descramble logging tool

The Descramble logging tool project started as a joint project between SINTEF-ICT and other Scandinavian organisations. SINTECF is an independent research organisation based in Europe that provides services through project work for various small and large companies. The Descramble logging tool was designed to measure temperature and pressure in super critical geothermal wells and in environments where temperatures and pressures are greater than 374°C and 218 bar respectively (Figure 27). The tool consists of high temperature electronics, has sensors, and makes use of custom-made batteries (SINTEF, 2015). During the research stage of the tool development, the following challenges were encountered:

- The development and manufacture of a Dewar (thermos) flask that performs efficiently and has a heat and pressure shield.
- The development and verification of a platform of electronics that enables functionality at temperatures above 200°C.
- The selection of a sensor and its integration.
- Testing battery solutions that allow for operation at temperatures above 200°C.

According to SINTEF (2015), the plan was for the tool to be tested in the laboratory and once tests are successful, field tests would be conducted in the drilled well in collaboration with global green energy producer Enel Green Power, which is coordinating the project. Due to its design and specifications, the Descramble logging tool was identified by the team as a potential instrument that could be adopted to measure hot hole temperatures and pressures in open cast mines due to its high temperature measuring ability. The cost of this device is not available as it is still in the early development phase.

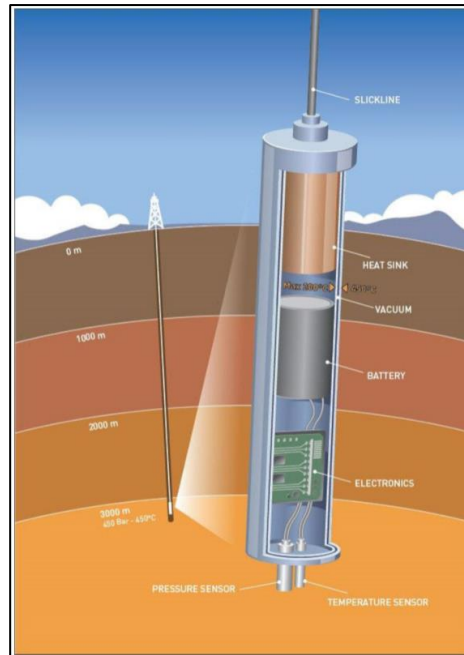


Figure 27: Descramble logging tool (SINTEF, 2015)

The Descramble logging tool may be applicable for in-hole air temperature measurements during pre-charging stages of the drill and blast cycle but will require significant customization for it to be applicable to hot hole management. It has an advantage over other devices in that it measures temperature and pressure. The subject of pressure monitoring in hot holes still needs further research.

3.3.3 MDT Thermistor String – NTC3K

The MDT Thermistor String – NTC3K is a device that is manufactured by a Canadian based company called Mine Design Technologies. The company develops products that can be applied in geotechnical and environmental environments. According to Mine Design Technologies (2021), the thermistor string is essentially a series of temperature sensors along the length of the cable (Figure 28). The position of the temperature sensors and the overall length of cable is determined by the customer at the time of order. The company provides thermistor strings with 1 to 19 temperature sensors (nodes) with an accuracy of $\pm 0.5^{\circ}\text{C}$ and a resolution of $\pm 0.2^{\circ}\text{C}$ as standard line items. The device has a temperature range of -40°C to 80°C . The product is a J-type NTC thermistor (made of chrome and constantan) with a nominal resistance of 3000 Ohm at 25°C . The string can be connected to a handheld thermistor readout to directly read the temperature in degrees Celsius ($^{\circ}\text{C}$). This product cannot be used in drill holes with water or debris. The device and the associated accessories cost a total of R23 478.76 (Ramjack Technology Solutions, 2021). The use of this instrument in the coal mines would require holes to be inspected for the presence of water before being used. Since hole depths are measured to check against the planned drill hole depth, this process could also be used to check for the presence of water in the hole. This instrument would have limited application particularly during the rainy season where holes might have water.

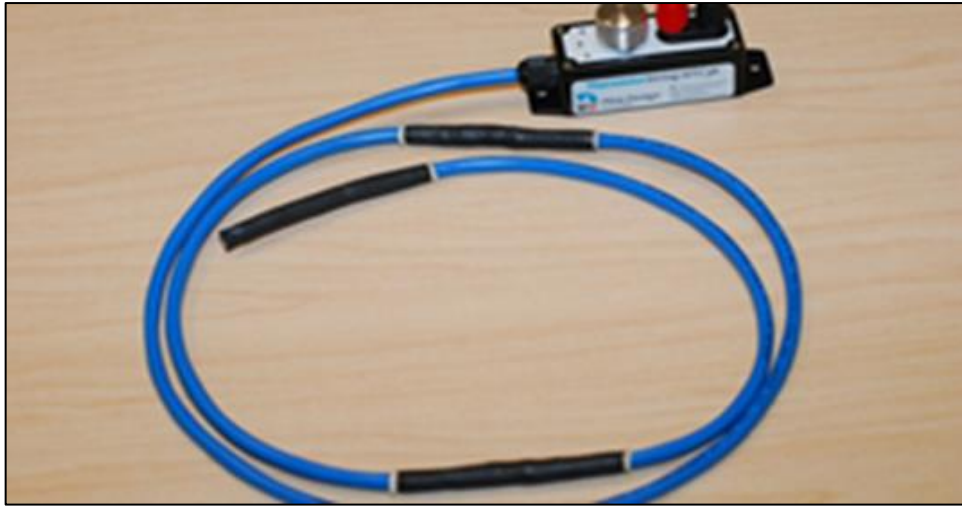


Figure 28: MDT Thermistor String - NTC3K (*Mine Design Technologies, 2021*)

In summary, this device is applicable for in-hole air temperature measurements from the time a hole is drilled until prior to charging.

3.3.4 Blast hole Temperature Logger Mk8 USB

The Blast hole Temperature Logger Mk8 USB is a measuring device developed by Insight Technical Support, a company based in Australia. It can be used to measure temperature in hot blast holes and blast holes on reactive ground (Insight Technical Support, 2021). The device consists of two parts, the logger unit, and an infrared probe (Figure 29). The logger unit uses a 250 mAh lithium battery that lasts 10 hours continuously. It takes 7 hours to charge the battery fully using a 5 V source or a mobile phone power bank. The infrared probe has a diameter of 40 mm, length of 110 mm and weighs 240 g. The probe is fitted with two infrared temperature sensors to monitor and correct for transient conditions and two ambient temperature sensors. Furthermore, it incorporates digital filtering to produce optimum results with respect to measurement time, settling time, noise, and impulse response.

One of its advantages is the internal memory where temperature readings are recorded and can be accessed using a USB interface. The infrared sensors are used to record temperature samples as the downhole cables move along a blast hole. Data such as time, date, hole ID and maximum temperatures are also recorded. The device also allows the user to set preferred logging intervals. The unit costs about R175 000.00 (Communication with a mine representative where the unit is being used to measure hole temperatures)



Figure 29: Blast Hole Temperature Logger Mk8 USB (*Insight Technical Support, 2021*)

The downhole cable incorporates Kevlar fibres for strength, stranded copper twisted pair conductors and gel treated fillers to prevent wicking, with a super tough polyurethane jacket in high visibility orange with meter markers. The device has audible beeps to indicate operation and a loud alarm which is triggered if either sensor reads over the set alarm temperature. It also has an emissivity of 95% and this can be adjusted depending on the rock conditions.

The device has the following functionality ranges as per manufacturers specification information:

- Ambient Temperature: 0°C to 75°C.
- Object Temperature: -20°C to 350°C.
- Spectral Range: 8 to 14 micrometres.

The specified accuracy of the sensors at different temperature ranges is:

- 20-40°C ---- +/- 0.3°C.
- 40-60°C ---- +/- 0.5°C.
- 60-120°C---- +/- 1.0°C.

The typical end to end accuracy of the system at different temperature ranges is:

- 0-100°C ---- +/- 1°C and +/- 1 digit.
- 100-180°C ---- +/- 2°C and +/- 1 digit.
- 180-240°C ---- +/- 3°C and +/- 1 digit.
- 240-350°C ---- +/-4°C and +/-1 digit.

This device is applicable to measuring the in-hole rock surface temperature during pre-charging activities. The device was tested and the results that include the temperature measurement duration are included in the Milestone 3 (SOP reviews, on-block observations and experimentation at the test) report.

3.3.5 QMR Temperature Log

QMR Blast (2021) defines this device as a temperature probe with 25 temperature sensors placed at 1 m intervals along the probe (Figure 30). The device can be connected to a PC

or a mobile device via Bluetooth. This connectivity allows for a temperature scan at 50 seconds and a reading of the last 24 hours of maximum temperatures. The device has a function that allows the user to erase the memory, therefore creating space for additional storage. The advantage of this device is that it provides the user with temperature data at 1 m intervals along the hole depth and this data is stored and can be exported. This feature will assist in understanding the temperature changes along the hole depth over time and thus it is suitable for application in the temperature measurements of hot holes. At the time of the compilation of this report, the manufacturer had not yet responded to the requests of the researchers for more information and the cost of the temperature log.



Figure 30: QMR Temperature Log

This device is applicable to measuring the in-hole air temperature during pre-charging activities of the drill and blast cycle. The device was tested and the results are included in the Milestone 3 (SOP reviews, on-block observations and experimentation at the test) report.

3.3.6 FLIR thermal imaging cameras

There are various Forward Looking Infrared (FLIR) cameras manufactured by Teledyne FLIR, a company from Europe. These thermal cameras include the FLIR TG267, the FLIR C2 and C3 (Pocket-Sized), the FLIR E5, E7 and E8 cameras that have WiFi and other more advanced models such as the FLIR E95 and FLIR T540. The features and prices of these handheld thermal cameras vary as shown in Table 8. There is no evidence that these cameras have been used in a mining environment for the management of hot holes, however the AEISG (2021), provides information on the pros and cons of these devices. The cameras are non-in-hole rock surface temperature measurement devices that can be used for the measurement of the in-hole rock surface temperature. The devices also display a picture of the heatmap of where they are pointed therefore, they are able to display some in-hole hotspots. However, since they are not in-hole temperature measurement devices, these cameras may omit some hotspots along the depth of the hole (Australasian Explosives Industry Safety Group (AEISG) Inc, 2021). Furthermore, the functionality of the devices is limited by the presence of steam, dust, fog and water.

Table 8: Selected FLIR thermal imaging cameras (Gothermal , 2021)

FLIR Camera Model	Image	Main Features and Cost
FLIR TG267 Thermal Imaging Camera		The camera detects cold and hot spots of temperatures between -25 °C and 380°C. The camera costs R7 999.00.
FLIR C3 Pocket-sized Thermal Inspection Camera With WiFi		The thermal images can be shared instantly over WiFi. The camera displays a spot metre and the minimum and maximum temperature to show the coldest and hottest areas. Price available on request by client.
FLIR E95 Thermal Inspection Camera		Key features include laser-assisted focus and temperature measurements of up to 1500°C. The camera costs R180 215.00.
FLIR T540 Thermal Inspection Camera		The camera is able to troubleshoot hotspots and find hidden faults. It features laser assisted autofocus and takes temperature measurements of up to 1500°C. The camera costs R260 861.00.

3.4 International temperature monitoring devices

3.4.1 QMR Hot Hole Indicator

QMR Hot Hole Indicators are developed by QMR Blast, an Australian based company that provides products, software and testing services for mines and mine related industries such as coal processors. These are low-cost disposable temperature indicators to identify hot holes (Figure 31)(QMR Blast, 2021). They are set to trip at a temperature of 55°C, but on request, the product can be adjusted to measure temperatures greater than 55°C. At the time of the compilation of this report, the manufacturer had not yet responded to the requests of the researchers for more information and the cost of the indicator.

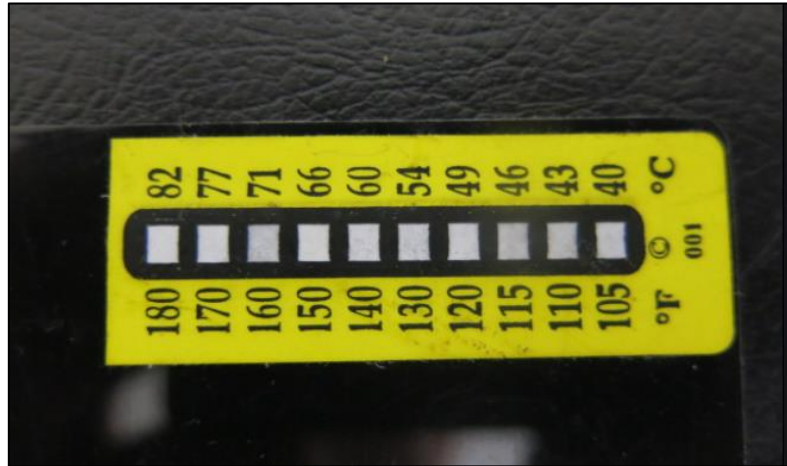


Figure 31: QMR Hot hole Indicator (*QMR Blast, 2021*).

Other advantages of the QMR Hot Hole Indicator are that it can be used in wet environments and multiple indicator cards can be used on a single dipping tape to measure the in-hole temperature at different locations along the depth of the hole. The disadvantage of this device is that the colour change may not be noticed if in-hole sensor is not left in a hole for an adequate time (Australasian Explosives Industry Safety Group (AEISG) Inc, 2021). Table 9 gives a summary of different temperature measurement and temperature monitoring devices.

Table 9: Summary of temperature measurement and monitoring devices.

Device name	Device Classification			Temp. range	Type	Summary of features	Price	Manufacturer	Country
	Stage at which device is used (pre-charging or during charging)	Method used to detect the temperature (in-hole or from surface)	Heat source measured (rock surface, air or emulsion temperature)						
Thermometer blast hole temperature probe	Pre-charging and/or during charging	In-hole	Air temperature	-50°C and 150°C.	K-type thermocouple	30 m long and has 0.5 m graduation markings. hot hole dipping tape that can be used for quality assurance checks on blast holes before loading	R4 800.00	MTI Group	Australia
Descramble logging tool	Pre-charging	In-hole	Air temperature	200°C	Thermos flask	designed to measure temperature and pressure in super critical geothermal wells and in environments where temperatures and pressures are greater than 374°C and 218 bar respectively	In development phase	SINTEF-ICT joint project	Scandinavia
MDT Thermistor String – NTC3K	Pre-charging	In-hole	Air Temperature	-40°C to 80°C	J-type NTC thermistor	Thermistor strings with 1 to 19 temperature sensors can be provided. Cannot be used in drill holes with water or debris	R23 478.76	Mine Design Technologies	Canada
Blast hole Temperature Logger Mk8 USB	Pre-charging	In-hole	Rock surface temperature	-20°C to 350°C	Infrared	Device can be used to measure temperature in hot blast holes and blast holes on reactive ground. Infrared probe has a diameter of 40 mm, length of 110 mm and weighs 240 g. Has an internal memory where temperature readings are recorded and can be accessed using a USB interface	R175 000.00	Insight Technical Support	Australia
Blast Hole Temperature Measure	Pre-Charging	In-hole	Air Temperature	55°C	Temperature sensors	The device can be connected to a PC or mobile devices via Bluetooth. Has temperature probe with 25 temperature sensors placed at 1 m intervals. temperature scanning at 50 seconds and reading of the last 24 hours of maximum temperatures (which takes 5 seconds).	R5000.00	QMR Blast	Australia
FLIR TG267 Thermal Imaging Camera	Pre-charging	From Surface	Rock surface temperature	-25 °C to 380°C	Infrared	This is the cheapest model found on the Gothermal website, a distributor of FLIR cameras.	R7 999.00	Teldyne FLIR	Europe
FLIR C3 Pocket-sized Thermal Inspection	Pre-charging	From Surface	Rock surface temperature		Infrared	The product (phone) is suitable for quick inspections rather than long inspections; since it is a phone, it has to be held on its edges rather than on a handle.	The cost is available on request	Teledyne FLIR	Europe

Camera with WiFi									
FLIR E95 Thermal Inspection Camera	Pre-charging	From Surface	Rock surface temperature	up to 1500°C.	Infrared	Key features include laser-assisted focus and temperature measurements of up to 1500°C.	R180 215.00	Teledyne FLIR	Europe
FLIR T540 Thermal Inspection Camera	Pre-charging	From Surface	Rock surface temperature	up to 1500°C.	Infrared	The camera is able to troubleshoot hotspots and find hidden faults. It features laser assisted autofocus and takes temperature measurements of up to 1500°C	R260 861.00	Teledyne FLIR	Europe
Kimo TT21	Pre-charging and/or during charging	In-hole	Ambient Temperature	Displays temperature measured	K-type	The Kimo TT21 constitutes of a compact, lightweight thermometer	R3 000	Emin	France
Sinometer DM6801B	Pre-charging and/or during charging	In-hole	Ambient Temperature	Displays temperature measured	K-type	Sinometer DM6801B is a k-type suitable thermometer that displays measured temperatures	R3 000	Sinometer	China
Fluke	Pre-charging and/or during charging	In-hole	Air Temperature	Displays temperature measured	K-type	The device constitutes of a K-type thermocouple and a multimeter that indicates the measured temperature.	R12 140	Electro Field Services (supplier) Fluke Corporation (manufacturer)	United States of America
Designs Unique Blast Eye Mk2	During Charging	In-hole	Emulsion Temperature	>100 °C	Temperature sensors	Multiple temperature sensors along the cable at 5m intervals. The cable is connected to a receiver unit that sounds a single alarm at 80 °C and continuous alarm at 100 °C	To be determined by customer specifications of customer	Designs Unique	South Africa
Ningi-Safeblast	During charging	In-hole	Air temperature and/or Emulsion temperature	>100 °C	Temperature sensors	Weighted cable with 10 sensors equally spaced out as per pre-described depth range. The cable is connected to an LED light pod that displays colour coded light indicators which represent different temperature ranges	The cost of the device is available on the customer's request.	Ningi Services	South Africa
Ningi-IR profiler probe	Pre-charging	In-hole	Rock surface temperature	-40°C to 125 °C.	Infrared	It has a handheld controller device which displays multi-point temperature reading across the blast hole circumference at a specific depth level. It has the functionality of an early warning alarm when escalating temperature readings are encounter. It has operating temperature range from -40°C to 125 °C.	The cost of the device is available on once development is complete and device is available.	Ningi Services	South Africa
PTM-806 Model Multi Thermocouple	Pre-charging and/or	In-hole	Air Temperature and/or Emulsion temperature	Maximum of 1200°C	K-type	Device is not designed to function in hot holes however it can be modified for hot hole applications. Auto power-off installed to preserve battery life. Built-in	Cost not disclosed	Test and Measurement Instruments C.C	South Africa

	during charging					microprocessor circuit ensures high accuracy with sampling time of approximately 1 second			
Fluke	Pre-charging and/or during charging	In-hole	Air Temperature	Displays temperature measured	K-type	The device constitutes of a K-type thermocouple and a multimeter that indicates the measured temperature.	R12 140	Electro Field Services (supplier) Fluke Corporation (manufacturer)	United States of America
Thermo-Hygrometer	Pre-charging	In-hole	Air Temperature	-20°C and 80°C	Infrared	Device stores approximately 8000 results including date and time.	R11 000.00	BAMR	South Africa
Hot hole Management System (HHMS)	During charging	In-hole	Air Temperature	-40 to 125°C	Temperature sensors	The device has multiple monitoring points along the cable which enables the user to profile a hole	Cost to be determined from customer specifications	Position NXT	South Africa
UNI-T handheld infrared thermometer	Pre-charging	From Surface	Rock surface temperature	-18 to 350°C	Infrared	Device measures the hole's rock temperature instead of ambient temperature, however, it may result in errors when used to measure temperatures in deep holes as the user may not clearly see the laser	R2500.00	CIB Partners	South Africa

4. Conclusion

Open cast mining operations often encounter hot mining blocks and/or spontaneous combustion in areas where mining occurs above old underground workings. The holes drilled in such areas often intersect such hot areas with temperatures of 40°C and above and these are defined as hot holes. As required by South African regulations, the hot hole temperatures need to be measured and monitored from the time they are drilled until charging to prevent premature detonation of the charged explosives.

A review was conducted to identify available temperature measurement and monitoring devices available in the local and international market. International manufacturers which were found to manufacture blast hole temperature monitoring and measuring devices included, MTI Group, SINTECF, Mine Design Technologies, Insight Technical Support and QMR. In South Africa, a few companies, that include AEL, BAMR, Position-XT and CIB Partners manufacture temperature monitoring devices that are suitable for hot holes temperature monitoring and measuring devices. Manufacturers such as Test and Measurement Instruments C.C. (TMI), BAMR and Ikaya Automation Systems manufacture temperature monitoring instruments for other applications that may not be as hostile as the hot hole environment. These instruments would have to be modified according to the customer's request for efficient use in hot holes and will vary from mine to mine due to the different mining conditions, mining designs, and risk assessment and management procedures. Other important considerations are the stage which the device is used in the drill and blast cycle, that is, whether the device will be used pre-charging or during charging. Devices used pre-charging are temperature measuring devices such as thermocouples and infrared instruments. Temperature monitoring devices are used to monitor the temperature change of explosives products such as emulsion during charging until prior to the setting-off of a blast. These devices should be cheaper in price as they are disposable as they are destroyed during the blast. A difficulty encountered during the review was obtaining device costs from manufacturers, particularly international manufacturers.

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Appendix B (Milestone 3: Standard operating procedure (SOP) reviews, on-block observations and experimentation at test site)

Executive summary

Introduction

This milestone reports on the results of the review of current hot hole management practices, testing of different temperature measuring and monitoring devices and testing of blasting accessories, amongst other parameters, as a way of managing the risk associated with hot holes. This was done through field testing at the experimental test sites and at active mining production blocks. The information gathered from the activities undertaken in this milestone will be amalgamated to compile a best practice guideline document for the management of hot holes in coal mining benches.

Methodology

A series of reviews, assessments and tests were conducted to understand the field of hot hole management on surface coal mines. Standard Operating Procedures (SOPs) from three surface coal mines were analysed and reviewed in detail according to specific themes to identify the various practices, innovations and accessories used in the management of hot holes. Visits were made to two of these mines to observe how the SOPs are implemented on actual production blocks. A fourth SOP for a surface coal mine, found in literature, was also reviewed. Although its contents may be outdated, key findings were identified from it. To gain a further understanding of the accessories used in the management of hot holes, different tests were performed at two test sites and on production blocks at a mine in the Emalahleni area.

Review of Standard Operating Procedures

SOPs from three surface coal mines and one international Code of Practice were reviewed. Some gaps and misalignments were found in the SOPs of the four mines with respect to regulation terminology. The definition of hot holes in some of the SOPs was found to be outdated, that is, it was not based on the latest (2018) version of explosives regulations from the Department of Mineral Resources and Energy (DMRE). However, this did not seem to influence the actual procedures in those SOPs. All the SOPs contained sections on the requirement to measure and record the temperature of holes, however, there was no explicit emphasis on that the in-hole ambient temperature should be measured along the depth of the hole. For all the mines, the responsibility of measuring the temperature of the holes was given to specific competent persons, depending on the complexity of the procedure.

All the SOPs that were assessed contained sections on the need to perform some form of a risk assessment that includes identifying hazards and declaring the area safe and limiting access to the bench. These activities are vital to hot hole management. For some mines, it was not clear whether bench preparation is conducted prior to or on the day of charging. For one mine, bench preparation is a standalone activity in the drill and blast cycle, and it is performed on the preceding day to charging. On this day, temperature measurements are taken and recorded, and are used as benchmark for further temperature

measurements prior to charging and blasting. According to the SOPs of the different mines, specific competent persons are responsible for bench preparation.

The SOPs review theme on *hot hole identification* had the purpose of establishing the methods followed in identifying hot holes and the associated accessories that are used. At one mine a pre-emptive risk assessment strategy is used to determine, in advance, whether the succeeding cut or blocks have the risks associated with hot holes. Furthermore, at this mine and in one other mine, the SOPs reveal that the risk of hot holes is associated with old underground workings. This is consistent with literature and observations made during the visits to the two mines. In all SOPs, the identification of hot holes occurs between the time of drill and the time of charging. The differences lie in the frequency of measurement and recording, the classification of the holes based on the measurements and the devices used to take the temperature measurements. At one mine, it is stated in the SOP that two independent temperature measurement devices should be used. Additionally, at this mine and at the other mines, it is prescribed in the SOPs that a Blast Eye monitoring device is used after charging of the holes to monitor explosive product temperatures.

According to the different SOPs, those holes that are found to be in the hottest classification band are sealed off and are not charged. There is a vast difference in the temperature of the holes that may be charged or sealed off at these various mines. For example, the SOP for one mine states that holes of up to 90°C may be charged and those above this temperature may be sealed off. In contrast, at the other mine, holes that have a temperature greater than 60°C are sealed off and not charged. Different accessories are prescribed in the SOPs for use in the hot holes of varying classification. These accessories include water, cooling agents, gas bags, foam expander plugs and PVC sleeves. The responsibility of overseeing the hole treatment process lies with the Blasting Supervisor or the Miner at the different mines.

Charging on a hot hole bench was also assessed. At one mine, the procedures for charging and blasting are centered around working safely and promptly at those areas in which hot holes are found. This is shown by the requirement to use three explosives trucks or two trucks with rapid reload system functionality in order to reduce the time spent on charging and subsequently, the time spent by workers on the block. In addition, personnel that are either not involved in the charging or those that are not trained and appointed are removed from the block. Other safety precautions contained in the SOP include the use of explosives that contain urea or inhibitors to charge hot holes, the charging and blasting of holes on the same day (no sleep-over holes). Detonators, which trigger at temperatures between 80°C and 110°C are not used and the drill holes are not stemmed on a blast block that has hot holes. These safety precautions are common in all the SOPs that were reviewed except for one precaution; the stemming of holes, which is practiced at one mine. Another common feature of the SOPs is the use of temperature monitoring device (the Blast Eye) to monitor the temperature of the emulsion after charging the holes. Monitoring of the in-hole emulsion temperature informs the evacuation procedure; the mining block is cleared if an alarm, that is set to trigger at specific threshold temperature (80°C), is reached.

Internationally, similar practices to those contained in the SOPs of local surface coal mines were identified. In Australia, a Code of Practice developed by explosives manufacturers,

quotes the Australian Standard (2187.2) definition for elevated temperature as material that is above 55°C. Materials above 55°C are divided into hot ground (ground with material above 55°C but less 100°C) and high temperature ground (material with a temperature of 100°C or more). In these areas, similarly to the DMRE regulations, the temperature should be measured along the length of the hole and the highest temperature measured should be recorded as the temperature for that particular hole.

On the identification of hot holes, the Code of Practice recommends that mine SOPs should contain a method that would be followed in the identification of which holes to measure, and when, and how often to test (e.g., test every hole, test every hole in a certain known hot area, test 24 hours apart to check for increasing temperatures), which instruments to be used and defining the site cut-off temperatures for the mine. Similar practices, including the classification of the holes into temperature categories, were also found in the local mine SOPs. Furthermore, the selection of a measurement device with a suitable temperature range and a measuring system suitable to the conditions (for example, infra-red may not be effective in wet holes or steaming holes) is recommended. Other recommended practices to enhance safety on a block with hot holes include using specific explosives products in line with the different temperature classifications and minimising the sleep time in hot holes to prevent the heating up of explosives products which may result in premature detonation.

Protocol for experimentation

Protocols or methodologies for conducting the tests were designed in collaboration with representatives from the mine. The tests were on gas bags, foam expander plugs, various temperature measurement and monitoring devices and sleeves made of Polyvinyl Chloride (PVC) material. Drill holes were monitored over time to determine how the ambient temperature in the holes evolves from the time the holes are drilled until prior to charging. The results and findings from these tests will contribute to the Best Practice Guideline for Hot Hole Management in surface coal mines, the fifth milestone of the project.

Assessment of current hot hole management practices

Hot hole management practices were assessed at two surface coal mines. At Mine A, most of the procedures implemented on the mining blocks were consistent with the SOP. There were some inconsistencies observed such as those regarding the sealing of holes. According to the SOP, those hot holes with a temperature that exceeds 90°C should be sealed off with foam expander plugs. However, on-field observations showed that holes up to 99°C were charged (and thus not sealed off); rather, those holes that were sealed off had temperatures exceeding 100°C. The misalignment may have been due to the lag between the adoption (and sign off) of new procedures and implementing these procedures on the ground. Similarly at Mine B, most procedures were implemented in line with the contents of the SOP. However, there were few exceptions that include the use of water and cooling agents in treating hot holes, which is found in the SOP but not practiced on the mining blocks.

Experimentation at test site and production blocks

Various temperature measurement and monitoring devices were evaluated according to the criteria developed in the test protocols. The results showed that there is no one device that is a perfect fit for the purpose of hot hole measurement and/or the monitoring of

emulsion in hot holes. This is attributed to the on-going innovations and design adaptations made to these devices for the unique field of hot hole management. Additionally, in the hot hole environment, factors such as dust, water, mud and smoke impede on the optimal performance of these devices. For example, an infrared device measures the in-hole rock temperature of the hole, which is useful since it is the rock that will be in direct contact with explosives during charging, however, the accuracy of the temperatures it dictates is affected by the presence of water, dust, and smoke and its temperature range is narrower than that of thermocouples. In contrast, thermocouples measure the in-hole air temperature, which may not be a true reflection of the highest temperature in the hole. Therefore, a balance needs to be found between the strengths and weaknesses of the different devices. This may be achieved through further technological design changes to the current instruments or alternatively, as practiced in one of the host mines, the use of two distinct types of temperature measurement devices (infrared and thermocouples) to provide more reliable in-hole temperatures characteristics.

The tests conducted to understand the behaviour of holes from immediately after they are drilled until prior to charging displayed varying results. In some mining blocks, the in-hole air temperature of the majority of the holes increased (with some holes increasing by up to 40°C) over a period of three days of observation. On one mining block, the in-hole air temperature of the majority of the holes decreased overtime, however, a minority of holes increased in temperature by up to 13°C. For all the blocks, there were some holes in which the temperature remained constant, with either a decrease or increase in the in-hole air temperature of 2°C or less. The results show that within a mining block, individual holes behave differently from the time of drilling until charging. The increase in temperature in the holes is a major safety hazard and the main factor of consideration in the management of hot holes. Even though the majority of the holes on a block may display minimal temperature changes, a single hole may be the cause of an incident due to a sudden large increase in temperature. This is the hole that may lead to the self-detonation or premature detonation of explosives on the block.

The results on a type of gas bag commonly used at the host mine suggested that these gas bags do not last for a period of 24 hours or longer in a hot hole of temperatures greater than 43°C. The gas bags failed by either deflating or rupturing. Thus, the use of gas bags, overnight, as a solid base for emulsion in holes that have holed through into underground workings (also known as *bhoboza* or breakthrough holes in mining vocabulary) or to seal off the bottom of venting holes needs a further review and more tests. These tests would include determining how much weight the gas bags can carry in such holes.

Tests conducted on foam expander plugs produced mixed results. The results and observations made at the mining blocks revealed that venting of holes is indeed stopped by the use of foam expander plugs but, when the foam is placed near the heat source in the hole, it burns, releasing white smoke, after which venting re-surfaces. Thus, the use of expanding foam, as a solid base for emulsion in *bhoboza* holes or to seal off the bottom of venting holes is not recommended. The foam plugs that were tested expanded by between 0.4 m and 1.5 m in the holes.

The PVC sleeve test results indicated that the PVC sleeves provided some form of insulation that prevented the explosives product (and water) from gaining heat from the surrounding hot hole walls. The temperature variance inside and outside the PVC sleeve

was maintained for a duration of up to 30 minutes in the emulsion tests, which was an adequate amount of time for completing the charging up and tying up processes in preparation for a blast. This duration was longer (more than 1.5 hours) in the tests conducted with the use of water. More tests on PVC sleeves need to be conducted for longer periods to determine the limits at which the temperature difference between the inside and outside of the sleeve is maintained. This would assist in determining the safe maximum duration to be spent on a block after the charging of hot holes.

Recommendations

The following recommendations are proposed based on the outcomes of the study:

- In order to ensure that all critical risks and issues are sufficiently covered, it is recommended that the SOPs for hot hole environments should be collaboratively developed by all key stakeholders that include technical personnel from the mines, in collaboration with key stakeholders that include the drilling and blasting personnel (who are directly involved with hot holes), temperature measurement and monitoring device manufacturers, manufacturers of explosives and accessories, manufacturers of hot hole management accessories (gas bags, PVC sleeves, foam expander plugs, cooling agents etc...) and representatives from the regulator.
- The temperature measurement and monitoring devices selected should ideally produce a profile of temperatures along the depth of the hole. This way the production team will get a clear indication of the position of the heat source, in instances where it is not at the bottom of the hole.
- The selected temperature measurement and monitoring devices should be user-friendly to avoid their abuse and incorrect use, which would defeat the purpose of enhancing safety.
- There should be clarity on the use of temperature measurement and monitoring devices, that is, how the instruments should be used to avoid incorrect measurements.
- Clear definitions that align with the current DMRE regulations and understandable hot holes terminology should be used in the procedures.

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List of Acronyms

ABDHT:	Above Baseline Drill Hole Temperature
AEISG:	Australian Explosives Industry and Safety Group
BERA:	Blast Eye Risk Assessment
BPG:	Best Practice Guidelines
COP:	Code of Practice
DMR:	Department of Mineral Resources (formerly)
DMRE:	Department of Mineral Resources and Energy
MHSC:	Mine Health and Safety Council
MMU:	Mobile Mixing Unit
PPE:	Personal Protective Equipment
PVC:	Polyvinyl Chloride
SLAM:	Stop, Look, Assess and Manage
SOP:	Standard Operating Procedure

1. Introduction

In line with the project aim which was to determine Best Practice Guidelines (BPG) for the management of hot holes in coal benches, the review of various Standard Operating Procedures (SOPs) for hot hole management in different mines was essential as it would assist the researchers to gain an understanding of the current practices in open cast coal mines. The review focused on relevant SOPs of local and international coal mines. Findings from the review were used to develop an experimentation protocol that was used as a guideline when conducting experiments at the two test sites. A risk management plan was prepared, and all potential risks foreseen at the experimentation sites were identified, assessed and mitigated. On-block observations were conducted at two open cast coal mines (on production blocks) that had supplied the research team with SOPs. The purpose for this was to assess the mine's current hot hole management practices against the SOPs provided. Lastly, experimentations of various blast accessories and temperature monitoring instruments were done at the two experimentation sites.

2. A review of standard operating procedures

The aim of reviewing SOPs was to gain an understanding of the various practices and accessories used in the management of hot holes in surface coal mines. The results of this exercise will be an input to the BPG (Milestone 4 of the project). The review of SOPs followed the principles of the thematic content analysis, a method used for analysing qualitative data (Anderson, 2007; Caulfield, 2021). A deductive thematic content analysis approach, which combines existing knowledge, such as literature findings and experiment results, with the preliminary information found on the SOPs, was used to conduct the review. This review process was made up of the following stages based on Anderson (2007) and Caulfield (2021):

- Familiarisation – conducting an overview of the received SOPs and making notes of important points.
- Coding – creating codes or units for analysis, based on phrases and technical language used in the SOPs and highlighting these for collation and further synthesis.
- Generating themes – building broader themes based on the developed codes and their patterns.
- Reviewing themes – assessing the themes against the SOPs to determine whether indeed the themes capture all the important content and renaming or restructuring categories where necessary.
- Defining and naming themes – specifying the scope covered by each theme and identifying a name that captures the key considerations.
- Writing up – compiling an analysis of the information from the SOPs.

Following this process, the SOP review was divided into four themes as shown in Table 10. Key to an SOP is the fundamental alignment to the relevant mining regulation. The Department of Mineral Resources and Energy (2018) stipulates that *at any surface mine, a written procedure is prepared and implemented, after consultation with the explosive's manufacturer or supplier, to prevent persons from being exposed to the significant risks associated with hot holes*. Furthermore, the Department of Mineral Resources and Energy (2018) stipulates that such a procedure must include:

- a) that a competent person appointed by the employer in writing should measure the temperature of the shot hole in the event of a significant risk of hot holes in that environment.
- b) that the temperatures of the shot holes should be measured *at any point throughout the length of the shot hole and recorded prior and during charging up operations* (Department of Mineral Resources, 2018).

The above-mentioned regulatory requirements were considered during the review of the SOPs. Additionally, the definition of hot holes, a common theme in all SOPs, was assessed against the definitions specified in the mine regulation. According to the Department of Mineral Resources and Energy, hot holes are defined as those shot holes, in a coal mine, *which after being drilled have an in-hole ambient temperature of 40°C or above, or show a temperature increase of 3°C* (Department of Mineral Resources, 2018). This definition is an amendment of the 2015 explosives regulations which define hot holes as *shot holes which after being drilled have an ambient temperature increase of 3°C*. There were some concerns raised about the completeness of the regulation with respect to whether (time) intervals at which the temperature increase of 3°C should be defined in the regulation or not, in light of fluctuating in-hole ambient temperatures. Further concerns were on whether the second part of the definition (“...or show a temperature increase of 3°C”) does not contradict (and thus supplements it) the first part which states that hot holes are those shot holes “...which after being drilled have an in-hole ambient temperature of 40°C”. For example, a question was raised as to whether, if the initial recorded in-hole ambient temperature is 30°C and the second temperature is 35°C (i.e. a temperature increase of 5°C, which is more than 3°C); would this be regarded as a hot hole or not (even though this particular hot is less than 40°C). The researchers consulted stakeholders from the mining industry that include the Mine Health and Safety Council (MHSC), the DMRE and the Coaltech Research Association. Ncube (2022), a stakeholder from the MHSC acknowledged that there may be a gap in the definition of hot holes in this regard, which may be filled by applying for a regulation amendment. Similarly, a representative from the DMRE suggested a regulation amendment as a solution, however, they also stated that there were no issues with the current regulation and that there was no need to insert any interval/period in the definition.

The other three themes of the SOP review are the identification of hot holes, bench preparation and treatment of hot holes. These themes are defined in Table 1.

Table 10. SOP review themes

Theme	Definition	Risk Management Hierarchy of Control (s)
Alignment with regulation	<p>This is the alignment of mine hot hole SOPs to hot hole management requirements stipulated in the explosives regulation. The theme seeks to answer the following questions:</p> <ul style="list-style-type: none"> • How is a “hot hole” defined in the SOP? • Does the SOP state that a competent person measures the temperature of hot holes? 	<ul style="list-style-type: none"> • Administrative

Theme	Definition	Risk Management Hierarchy of Control (s)
	<ul style="list-style-type: none"> Does the SOP stipulate that hot hole temperatures should be measured throughout the length of the hole and recorded prior and during charging up activities? 	
Hot hole Bench Preparation	<p>This is specific to the activities conducted on the bench in preparation for charging up and blasting in a hot hole environment. The theme seeks to address the following questions:</p> <ul style="list-style-type: none"> When is bench preparation conducted (on the same or different day as blasting)? What does bench preparation, with respect to hot holes, entail? Who is responsible for bench preparation? 	<ul style="list-style-type: none"> Personal Protective Equipment (PPE) Administrative Engineering
Identification of hot holes	<p>This is the process of identifying where hot holes are located, generally on the mine and specifically on a bench. The theme seeks to answer the following questions:</p> <ul style="list-style-type: none"> What is the procedure/method for identifying hot holes? When are hot holes identified (in advance, actively or not conducted)? What instruments or technologies are used to identify hot holes? Who is responsible for identifying hot holes? 	<ul style="list-style-type: none"> Administrative
Treatment of hot holes	<p>The treatment of hot holes refers to the reduction of the risk posed by hot holes through administrative, engineering, substitution or elimination controls. The theme seeks to address the following questions:</p> <ul style="list-style-type: none"> What is the procedure for treating hot holes? What accessories are used for the treatment of hot holes? Is the procedure adequate in reducing the risk associated with hot holes? Who is responsible for the treatment of hot holes? 	<ul style="list-style-type: none"> PPE Administrative Engineering Substitution Elimination
Charging and blasting of hot holes	<p>This refers to the charging procedure to be followed when hot holes are encountered on the bench. The theme seeks to address the following questions:</p>	<ul style="list-style-type: none"> PPE Administrative Engineering Substitution Elimination

Theme	Definition	Risk Management Hierarchy of Control (s)
	<ul style="list-style-type: none"> • What procedure is used to charge hot holes (adequate accessories)? • Which explosives products are used? • After charging, are hot holes stemmed? • Who is responsible for charging hot holes? 	

2.1 A review of local SOPs

Initial requests were sent to local coal mine representatives seeking SOPs used at respective mines and the response rate was low. This led to delays in the completion of project milestones, however, further engagements with various mining industry stakeholders resulted in the attainment of SOPs from three local surface coal mines, which are currently having some challenges with hot holes. A list of the mine representatives contacted by the researchers during the SOP gathering stage of the project was compiled but is not included in this report for ethical reasons. It is noteworthy that for ethical reasons, the three mines will be referred to as Mine A, Mine B and Mine C in this report. Moreover, sections of another South African surface coal mine (referred to as Mine D in this report), that were included in the Best Practice Guideline for the prevention and control of spontaneous combustion (Phillips, et al., 2011), were also reviewed.

2.1.1 Alignment with regulation

2.1.1.1 Mine A

In the SOPs for Mine A, hot holes are defined as *shot holes which after being drilled have an ambient temperature increase of 40 degrees Celsius*. This definition is not entirely aligned with the definition stipulated in the explosives regulation by the Department of Mineral Resources and Energy (2018). The phrase in the SOP of Mine A that states “...an ambient temperature increase of 40 degrees Celsius” contradicts the phrase “...a temperature increase of 3°C” stipulated in the regulation. However, it seems that the inaccuracy in the definition is not a technical error because in other sections of the SOP (identification of hot holes, classification of hot holes based on, sealing of holes etc...), the definition of hot holes as stipulated in the regulation is adhered to. In the SOPs from Mine A, it is stated that the Blast Supervisor is the responsible person for measuring the temperature of the holes and this is in line with regulation that requires a competent person to be responsible for this process. This responsibility changes based on the level of intervention needed on the block. Other activities on a hot hole block are implemented by different competent persons that include the Blasting Assistant, the Blaster and the Drill and Blast Superintendent. It is not explicitly mentioned in the SOP from Mine A that the temperatures of the shot holes should be measured “...at any point throughout the length of the shot hole...” as required by regulation. Furthermore, the SOP does not contain information on how the different temperature measuring instruments should be used on a block. This is important as it would define whether indeed temperature is measured throughout the length of a hot hole in accordance with the regulation.

2.1.1.2 Mine B

Mine B defines hot holes as *shot holes with temperatures between 40°C and 60°C*. The definition is partly misaligned with that stated by Department of Mineral Resources (2018). The definition appears to exclude those drill holes with temperatures greater than 60°C as being hot holes. In addition, the definition for Mine B omits the phrase in the regulatory definition which considers those drilled holes that “...*show a temperature increase of 3°C*” as hot holes. The SOP stated that a Miner (with a Competent A certification) should take hole temperature measurements, however it does not highlight whether the temperatures should be measured throughout the hole length. It further stated that if hole temperatures reduce below 60°C, the hole may be charged but a final temperature check should be done before charging. This shows that hole temperatures are taken before and during charging.

2.1.1.3 Mine C

At Mine C, all personnel involved in blasting operations are expected to be familiar with the relevant provisions of the Minerals Act and Regulations, and the exemptions granted by it. Failure to adhere to the Minerals Act and Regulations will result in disciplinary actions. Mine C defines hot holes into two categories, namely hot holes and extreme hot holes. Hot Holes are holes with a temperature that exceeds 2°C above the Above Baseline Drill Hole Temperature (ABDHT) of an area. A value of 28°C is used as the ABDHT at Mine C. According to the regulation, the lowest temperature at which a hole is considered hot is 40 C, and Mine C starts at 30°C. This shows that Mine C takes extra precaution when considering hot holes. The SOP definition of hot holes at Mine C does not, however, include those drill holes, in which the in-hole ambient temperature increases by 3°C as defined in the Department of Mineral Resources (2018) regulations. Hole temperatures are taken at the top, middle and bottom of the hole and are recorded prior to charging. Additionally, holes with hottest temperature are also recorded prior to charging. This is in line with the requirement to measure the in-hole ambient temperature *at any point throughout the length of the shot hole and recorded prior and during charging up operations* as stipulated in the regulation.

2.1.1.4 Mine D

Information on Mine D was not extracted from the mine’s SOPs but from a Best Practice Guideline for the prevention and control of spontaneous combustion (Phillips, et al., 2011) that included sections from the mine’s SOPs. Mine D specifies that any hole with a temperature exceeding 60°C is treated as a hot hole. Furthermore, it defines a hot hole area as one with holes that have temperatures above 60°C; holes releasing smoke or steam and holes where temperature increases by 10°C above 40°C. The definition of a hot hole is not aligned with that stipulated by the Department of Mineral Resources as it does not consider holes with temperatures less than 40°C. Mine D’s hot hole definition may have been updated since its publication in 2011, which was prior to the publication of the current Department of Minerals (2018) Regulation. It is noteworthy that the definition of hot holes for Mine D considers hot holes as those holes with a temperature increase of 10 °C above 40 °C compared to the regulation definition that considers those drilled holes that “...*show a temperature increase of 3°C*” as hot holes”. It would be worthwhile to understand and consider the reasons for the choice of these values used by both organisations for future regulation amendments. Upon completion of charging, the Miner is responsible for the destruction of remaining explosives. Excess explosives and

accessories should be destroyed according to the Manage Excess Opencast Explosives procedure. The packs of explosives accessories may be returned to the magazines.

2.1.2 Hot Hole Bench Preparation

2.1.2.1 Mine A

The procedure followed in preparing a hot hole block for subsequent charging and blasting is similar to the procedure for a normal block. It involves activities such as identifying hazards and declaring the area safe, access control and gas detection, which is of relevance to hot hole risk management. An inspection for testing of noxious gases such as carbon monoxide (CO) and carbon dioxide (CO₂) and fumes is conducted on the block using a calibrated instrument and the results are recorded on a safe declaration form. According to the SOP, brown, yellow and white fumes are toxic if inhaled and indicate rapid oxidation. The SOP includes a procedure to be followed in the event that noxious gases exceed the limit: all members of the team evacuate the block to a safe area and put on self-contained self-rescuer kits. Upon returning to the block, the procedure requires the sealing off of possible sources of smoke and hot holes using expander foam plugs. The gas measurements are taken again, and the block is declared safe by the blaster when levels have subsided to less than the limits, only then will the team take off the gas masks. The Blaster (a Competent A certificate holder) inspects the block and completes the safe declaration inspection form if the area is safe for mining activities to commence. Preparation of the block for blasting involves measuring the temperature of holes, recording the information on a data sheet and marking the holes with the relevant temperature classification tags. These are good practices in the management of hot holes. The data on the holes is used to design a blast to be carried out on the succeeding day. Marking the holes with tags is a visual indicator of the level of risk associated with the particular holes and it also allows for continuity in sharing of information and data on holes between different shifts. It is not clear whether the practice to separate the preparation day from the blasting day outweighs the risk of the temperature of hot holes increasing between these days. Bench preparation on the day of blasting includes ensuring that there are enough bulk explosives (and trucks) prepared for the block and that these are used on the same day utilised to charge holes in a hot area.

2.1.2.2 Mine B

Before blasting activities commence, the blasting area is declared safe by a Miner with a Competent A certificate, who completes the safe declaration inspection form. Additionally, the Miner and the crew must conduct the Stop, Look, Assess and Manage (SLAM) risk management process. Based on the holes measured and counted, areas that will be charged should be barricaded and the barricade should be erected at distances greater than or equal to 15 m from the hole that will be charged. Only authorised vehicles (Mobile Mixing Unit (MMU) and stemming machines) are allowed to enter the blasting area while other vehicles park at a minimum distance of 15 m from holes being charged. The SOP did not explicitly highlight whether a hot hole block is prepared a day before or on the day of blasting. However, observations made at Mine B indicated that a block is prepared, charged and blasted on the same day. This may be a good practice as it reduces the risk of in-hole temperature increases over time. On the contrary, the preparation of a block and the measurement the temperature on the preceding day allows for the gathering of data that may be useful in adapting a blast design to the conditions.

2.1.2.3 Mine C

According to the reviewed SOP for Mine C, the procedure for bench preparation is particularly different when charging either hot or extreme hot holes. However, there are some exceptions mentioned which include exclusion of the use of in-hole detonators for both hot and extreme hot holes. Sleeping over of explosives is also not allowed in either type of hot holes, therefore, the Blasting Foreman should ensure that the correct quantity of explosives and MMUs is arranged prior to the commencement of blasting. Pre-splitting on overburden is also not allowed. As part of the preparation for charging extreme hot holes, a risk assessment is conducted. The risk assessment includes additional measures such as closing out the area before charging commences to reduce extra movement in and out and around the block. A risk. Guards should be placed in position to prevent unauthorised entry into the danger zone. The guards should be clearly visible to any person or vehicles approaching the bench to be blasted. Barricades should also be in position to prevent unauthorised entry to clearly mark the perimeter of the danger zone. All equipment and cables should be withdrawn to a safe distance from the hot hole blasting zone. Should there be a need to close-off the public area, the Miner will ensure that they are evacuated.

2.1.2.4 Mine D

Preparation for blasting a hot hole bench involves identifying and tagging the holes to indicate the hole number, depth and the measured temperature. The following temperature classifications are used for the tags:

- White tag – below 40°C.
- Green tag – between 40 °C and 60°C.
- Red tag – above 60°C.

Marking the holes with tags is a useful practice in that it provides a visual record of the parameters of the hole and thus the risk associated with the particular hole. In addition, it allows for continuity in sharing of information and data on holes between different shifts

2.1.3 Identification of Hot Holes

2.1.3.1 Mine A

At Mine A, a pre-emptive risk assessment strategy is used to determine, in advance, whether the succeeding cut or blocks have the risks associated with hot holes. According to the SOP from Mine A, any mining block that is above old underground workings is considered to have a significant risk of the presence of hot holes. Additionally, there is a general assumption that all mining blocks contain reactive material until tests for reactivity have been conducted to prove otherwise. These are extra precautions taken by the mine to better manage risks associated with hot holes ahead of time. The Drill and Blast Superintendent is responsible for the identification of areas that have the possibility of hot holes and/or reactive ground whereas, accountability for the process lies with the Operations Manager.

The procedure for identifying and measuring the temperatures of hot holes at Mine A is split into 2 days, the preparation day and the day of blasting. Additionally, the SOP prescribes that two independent probes should be used for temperature measurement however, there is no information on the type of device (thermocouple, infrared, laser etc...) to be used or how it is used. A variation of more than 5°C between the readings of the two

probes requires re-testing by a Blasting Supervisor, continued monitoring of the hole using a blast eye device and charging of the specific holes last.

On the preparation day the following activities are conducted:

- Measurement of the temperatures of the holes on the block (these holes are charged on the next (charging and blasting) day.
- Recording of the hole temperature measurements on a Blast Hole Data Sheet.
- Tagging of the hot holes according to the classification shown in Table 5.
- Submission of the blast hole data sheet (containing hole temperatures and depths) to the Drilling and Blasting Mining Engineer.

Table 11: Classification of hot holes based on measured temperature at Mine A

Colour of Tag	Hole Temperature	Hole Type
White	<40°C	Cool Hole
Yellow	Between 40°C – 54°C	Hot Hole
Red	>55°C	Hot hole

On the day of charging and blasting the following activities are conducted:

- Measurement of the temperature of all holes on the block.
- Recording of the hole temperature measurements on a new Blast Hole Data Sheet.
- Updating the tags to correspond with the new temperature readings, where applicable.
- Informing the Blasting Supervisor of any hole temperature variation between the preparation day and the charging day.

2.1.3.2 Mine B

The SOP for Mine B indicated that the presence of hot holes is identified by assessing all areas to be mined for spontaneous combustion and the presence of holes that are beyond the safe chargeable temperature particularly in previously mined underground workings. The details of the assessment are not described in the SOP. The SOP does not mention temperature measuring instruments used to identify hot holes.

2.1.3.3 Mine C

Mine C classifies hot holes according to categories namely hot holes and extreme hot holes. The procedure for the identification of each category is different.

Hot holes

The following procedure is followed in the identification of hot holes:

- All hole temperatures are measured at the top, middle and bottom of the hole and should be recorded prior to charging. Holes with hottest temperature are also recorded prior to charging.
- Hot holes identified using a Blast Eye Risk Assessment (BERA) however the details of the assessment were not outlined in the SOP for Mine C.
- Every 3rd hole along the edge of the low wall/buffer zone. This area is more likely to heat up because it is more exposed to air/venting.

Extreme hot holes

The procedure followed at Mine C for the identification of extreme hot holes is as follows:

- The Miner will measure and record the temperature of the hot hole on the Drill Hole and Charging Record Sheet prior to blasting.
- The Miner in conjunction with the Blasting Foreman will review the Mini Risk Assessment to determine the relevant charging procedure to be followed.

The SOP for Mine C highlights that temperatures are taken for hot and extreme hot holes. It does not specify which instruments are used to measure these temperatures.

2.1.3.4 Mine D

The procedure used in the identification of hot holes at Mine D indicates that all the holes located within 100 m of a hole with a temperature greater than 60°C, are treated as hot holes and their temperature should be measured and recorded daily. An additional strategy used to identify hot holes is to drill test holes (which hole through to underground workings) at particular locations (north-west corner) on every block, at two strips ahead of the current block. Data about the holes including temperature recordings should be signed off by the Mine Overseer and Colliery Manager. There was no indication of which instruments are used to measure the temperature of the holes.

2.1.4 Treatment of hot holes

2.1.4.1 Mine A

The procedure to be followed in the treatment of hot holes on a block is defined by the highest hole temperature (up to 80°C) measured on the block. The SOP prescribes the procedure to be followed for the treatment of holes with a temperature above 40°C but less than 80°C.

The SOP from Mine A states that those hot holes with a temperature above 55°C and less than 90°C will be considered for treatment with water and a cooling agent. If the holes cannot be cooled with water to less than 80°C, they will not be charged. Those hot holes with temperatures above 90°C are sealed off by inserting a foam expander plug at the collar of the hole and they are recorded on the Blast Hole Data Sheet. Holes that hole through to underground workings and those that are venting are sealed off with foam expander plug. It is the responsibility of the Blasting Supervisor to ensure that these treatment processes are followed.

At Mine A, in addition to the procedure for surface charging, there is a procedure for the treatment of hot holes, specifically with water and Polyvinyl Chloride (PVC) sleeves. The processes followed in identifying areas with possible hot holes and the measurement of the temperature of holes is the same in both sets of procedures.

Treatment of hot holes with water

According to the SOP, hot holes may be treated with water on both the preparation day and the day of charging and blasting. On the preparation day, the treatment of hot holes with water commences after the identification of hot holes and the measurement of temperature, as discussed in section Mine A. After the holes have been identified, the Blasting Supervisor measures the pH of the water in the bowser and records it in the blast report, according to the procedure for the measurement of the pH of water. The

measurement of the pH of water is relevant for areas that may have reactive ground material, which may react with the water. The procedure for the measurement of the pH of water requires that the pH meter is calibrated daily for accuracy of readings and that the water source be monitored regularly (there is no specification on the frequency of regularity). Additionally, this procedure, prescribes that the pH of the water source should not be less than a pH of 2 (if it is indeed less than a pH of 2, this should be reported to the Production Superintendent). It is also stated that if the hole already has water in it, the Blaster (the responsible person for this procedure) has to measure the temperature and the pH of the water. The water is pumped out of the hole if the pH is found to be less than 2, after which the pH of the water is measured again. In treating the holes on the preparation day, water is filled to the collar of the hole and left overnight. The risk associated with this process is steaming and/or the production of water gas, which often occurs in holes above 80°C. According to (Phillips, et al., 2011), the water gas, which is made of two flammable gases, carbon dioxide and hydrogen is a source of ignition and a hazard to personnel working in that environment.

On the day of blasting, two scenarios regarding the treatment of hot holes with water arise. The first scenario is the continuation of the treatment of hot holes from the preparation day. This scenario involves the measurement of hole temperatures, marking on the plan of the holes that require further treatment (those holes above 80°C) and subsequently, treatment by re-filling of the holes with water where applicable, subsequent to the measurement of the pH of water in the water bowser and that of the water in the hole. The measurement of the pH of in-hole water is done for every two holes in a line on the block. After treatment of the hot holes with water, the temperature is measured again. If a hole has been cooled down to below 80°C, normal hot hole charging commences. If the temperature of a hole remains above 80°C after treatment with water, the hot hole must be sealed. It is not specified what accessories should be used to seal this type of hole. However, in the SOP, it is stated that foam bags should not be used in holes that already contain water as doing so limits their full performance in sealing holes.

The second scenario, on the day of blasting, is for those holes that need treatment with water on this particular day but were not identified as requiring treatment on the preparation day. The procedure to be followed is the same as that for treatment of hot holes on the preparation day. Those holes with temperatures above 80°C or those that continue venting after treatment are sealed off.

In the event that a water bowser is not available for use on the block, the issues should be reported to the Production Superintendent by the Blasting Supervisor, who is responsible for implementing this procedure. Following this, an evaluation should be carried out to determine whether a blast should continue based on the number of available and/or sealed off holes.

Although, there is a procedure for the treatment of hot holes with water, it was found, during observations, that this practice is not implemented due to results from previous tests which indicated that the use of water is not an effective and viable means to treat hot holes.

Treatment of hot holes with PVC sleeves

The SOP states that PVC sleeves are installed on the charging day in holes that:

- are venting and with a temperature below 80°C.
- are cracked.
- penetrate through, into known hot underground workings or in blocks with holes of temperatures less than 80°C.
- pillar holes.

A wooden stick of 20 mm diameter and 300 mm length is hung across a hole, holding the PVC sleeves hanging in place. The sleeves are of fixed lengths; the correct sleeves should be inserted into holes of corresponding depths. A maximum air deck of 1 m is left at the bottom of the hole. The Blasting Supervisor is responsible for implementing this procedure.

The sleeve is then lowered slowly down the hole and a blast monitor device is placed inside the sleeve to detect temperature change. The holes in which a PVC sleeve is inserted are charged with explosives product from the bottom of the hole in an upwards direction using a pipe. In these holes, stemming may be used, following the standard stemming procedure. During charging, if a sleeve fails, the incident should be reported to the Production Superintendent. The SOP further states that the hot holes in which PVC sleeves are installed should be free of any gas bag or foam expander plug. The use of PVC sleeves at this mine was in the pilot stage at the time of the assessment. Further changes may have been made to the SOP in this regard.

2.1.4.2 Mine B

Hot holes are treated in various ways:

- Holes with temperatures >60°C should be sealed off. The SOP did not specify the accessories used to seal off the hole.
- If a hole with temperature >60°C cannot be sealed off, it should be cooled down with water and a cooling solution. A second hole should be drilled 2 m from the initial hole at a depth 2 m shorter than the initial hole to avoid, presumably, breaking through to the underground roof.
- Blast holes that have penetrated old underground workings or cavities are not charged but sealed off with drill chippings and/or sand. A second hole should be drilled at a depth 2 m shorter than the initial hole.
- Holes that vent or burn before blasting commences must be sealed off. A second hole should be drilled at a depth 2 m shorter than the initial hole.
- The Miner is responsible for the treatment of hot holes, with the assistance of the Blasting Assistant.
- Redrilling a hole 2 m shorter eliminates the risk of dealing with a hot hole but this procedure may not necessarily be adequate in treating hot holes due to the undulating geology at Mine B and the fact that highest temperature may not necessarily be at the bottom.

It is not clear how the drilling of a hole 2 m adjacent to those that breakthrough, vent or burn is effective in the treatment of hot holes. This is in light of the fact that the hottest spot in a hot hole can be located at any position along the depth of the hole (although, based on observations it mostly is). Furthermore, especially in seams that are undulating or at an angle to the horizontal, a hot spot may still be intersected with 2 m away from the initial hot hole.

2.1.4.3 Mine C

The SOP for Mine C did not include a procedure for the treatment of hot holes. The only procedure that was highlighted was for the treatment of extreme hot holes, and is as follows:

- The Miner and Blasting Assistant should, based on the temperatures measured, determine if cooling is required. If hole temperature is greater than 54°C (60°C minus 10% margin of error), the hole should be cooled, and temperature measurements should be retaken.
- The Miner with Blasting Assistants should insert the blast eye in:
 - The hottest hole in the first line to be charged.
 - Two hottest holes that are not in the first line.
 - Any other hole deemed necessary.
- The Miner must ensure that all personnel pay attention to any blast alarm sounding.

The inclusion of a 10% margin of error is a good practice that may be further investigated to determine a more accurate value. As it is, this margin of error accounts for technical temperature measurement instrument errors, factors such as the skill and experience of the user and changes to the weather. The practice to insert the Blast Eye in selected holes leaves room for the risk of unforeseen ignitions. In the event that a hole with no Blast Eye (or any other temperature monitoring device) inserted, experiences a rapid increase in temperature, personnel would not be aware timeously. Furthermore, the use of the Blast Eye device, which only measures the temperature at one point in a hole, may give a false sense of security if it is placed at a point other than a hotspot in a hole.

2.1.3.1 Mine D

At Mine D, immediately after the holes are drilled, they are initially sealed with a cone and expanding foam at the bottom of the hole to prevent the ingress of air. The cost implications of using this method resulted in its discontinuation and the adoption of air bags to seal these holes. There were no other accessories mentioned for the treatment of hot holes, however, blasting methods such a buffer blasting was practiced to reduce the surface area of the heat source.

2.1.5 Charging and Blasting of hot holes

2.1.5.1 Mine A

The procedure for charging requires the preparation of the block before the different charging practices are implemented. Preparation of a hot hole block includes addressing issues that affect both health and safety of personnel and productivity of a mine. The practices include ensuring that the bulk explosives prepared for the block are used on the same day and that at least three explosives trucks are utilised to charge holes in a hot area. Alternatively, instead of the three explosives trucks, two bulk trucks with rapid reload system functionality may be used. The procedure also prescribes that backup trucks should be available in case of breakdowns. In preparing the block for charging, the blasting team is assigned tasks to perform for the duration of charging and all personnel that are either not involved in the charging or those that are not trained and appointed are removed from the block.

Charging proceeds according to instructions from the Drill and Blast Mining Engineer. The charging instructions are based on the (highest) temperature and reactivity classification chart provided in the SOP.

In the SOP for Mine A, there are general recommended practices to be followed when charging a block that has hot holes. The practices include:

- No sleeping over of hot holes is allowed.
- Only explosives that contain urea or inhibitors as supplied by the explosives manufacturers may be used to charge hot holes.
- Ensure sufficient MMUs are available (sufficient backup in case of breakdowns).
- Stemming may be used as prescribed in the procedure.
- No holes on a hot hole blast block may be charged with detonators (because detonator triggers at temperature between 80°C and 110°C).
- Every employee in the working area shall wear safety protection as prescribed.
- Blasting supervisor will be present on the blasting block at all times while hot hole charging is in progress.
- Top charging should be implemented, and priming should be done with a cord and a booster.
- Hot holes with temperatures above 55°C are charged and a blast eye (temperature monitoring device) is inserted in the hole during pumping of explosives product at the position of the highest temperature in the hole. However, identifying this position on the charging day may prove to be an inaccurate practice. The blast eye may end up being placed in a different position in the hole that might not necessarily be hot, thus giving a false sense of safety. The blast eye is blasted with the rock.
- During charging, the blasting radius is cleared, and some of the team personnel are moved from the block to a safe location. The rest of the team assists with finalising the charging process.
- The lead line is then reeled out to the initiation point after the area has been declared safe by the Blasting Supervisor and the remaining team members are removed from the block. Subsequently, the blast is initiated.
- The use of water or cooling agents to cool down holes is allowed for holes with temperature up to 80°C.
- If there is any sign of heating, hole starts to smoke or vent or sets off a hot hole monitor above 80°C (continuous siren), all personnel must be removed from the blast block and follow the procedure for premature reaction and detonation procedure.
- No persons to approach a hole that is fuming, venting or steaming abnormally or where the alarm has activated above 80°C on a charge hole.
- Remove all personnel from the blast block to a safe distance, barricade the area and report to the production Superintendent-Blasting.

2.1.5.2 Mine B

The charging procedure for hot holes in Mine B includes priming, charging, stemming and blasting.

Priming of hot holes:

- Hot holes are primed with powercord and pentolite boosters.
- Detonators are not allowed for priming.
- Holes shorter than 2 m and “holed” holes are not primed.

Charging of hot holes:

- Holes with temperatures $>60^{\circ}\text{C}$ should be sealed off however, in situations where they ought to be charged, permission should be requested from the Mine Manager
- Hot holes are charged last on a bench.
- Holes with temperatures $<60^{\circ}\text{C}$ may be charged but final temperature checks should be done just before charging.
- The Miner should ensure that sufficient explosives are available for charging holes hot holes.
- Personnel and equipment must be removed outside the blasting radius before hot holes are charged on the bench. Only the explosives truck will remain within the barricaded area.
- Charging of drill pattern should not be done in a random fashion but where practical, charging should start at the initiation point with holes in the first row charged first, from the free face to the high wall or solid face.
- Sufficient reload and MMU capacity must be available on the bench before charging commences.
- Areas with potential hot holes must avoid sleep over of explosives.
- ANFO is not allowed, only emulsion-based explosives are pumped in hot holes.

The blast eye device is used during charging to monitor emulsion temperature changes:

- The Miner should insert the blast eye in holes before charging to monitor temperature changes during charging.
- The blast eye is inserted in holes that will be charged first; holes with hottest temperature before charging; holes identified using the Blast Eye Risk Assessment; and every third hole along the edge of the exposed low wall/buffer zone.
- If the blast eye sounds intermittently, it means the emulsion has reached 60°C , therefore charging is immediately stopped, and the bench should be squared off and blasted.
- If the blast eye sounds continuously, it means the emulsion has reached 80°C , and charging must be immediately stopped and the bench must be blasted. Hot holes are stemmed however, no stemming is allowed after the blast eye siren has sounded.

2.1.5.3 Mine C

The charging and blasting procedure for the hot holes followed at Mine C is categorised according to the type of hot hole and furthermore per stage of charging and blasting.

Hot holes

Prior to charging the Blasting Foreman should ensure the following:

- Sufficient explosives are arranged for the day's blast.

- Determine the number of MMUs available and ensure that there is a minimum of two MMUs available.
- The Miner must determine the number of holes that can be charged based on hole depth.

Priming

The priming procedure used at Mine C to prime hot holes states that blast holes should either be top or middle primed. Bottom priming of blast holes is not allowed. The use of in-hole detonators is also not allowed.

Charging

Mine C procedure for charging hot holes is as follows:

- No pre-splitting is allowed on inter-burden.
- Charging should be done in a squaring off sequence.
- The escape route should always be available.
- Charging should be done at a distance from the high wall.
- Only explosives & stemming vehicles should be on the bench.
- No sleep overs of charged holes is allowed.
- Holes are stemmed.
- The blast eye device is inserted in holes. The miner should notify the team to remain alert to the blast eye alarm throughout the charging process.
- If the blast eye rings an alarm sounds intermittently, charging and stemming should be immediately stopped.
- Sleeping over of explosives is only allowed in extraordinary circumstances which may include equipment breakdown or adverse weather conditions. The closing procedure should be followed.

Extreme hot holes

The Miner/Blasting Assistant is responsible for mid-priming holes below 120°C and top priming holes above 120°C according to the initial measurements. Holes with a temperature that is above 50°C at Mine C are charged and primed as discussed below:

- To ensure single day charging, the Blasting Foreman should arrange sufficient bulk explosives and determine the number of MMUs available for the blast.
- Sufficient reload and MMU capacity should be available on the bench prior to the commencement of charging procedure. A minimum of two MMUs is required to ensure consistent supply of bulk explosives during charging.
- The Miner must determine the number of extreme hot holes that can be charged based on the number and depth of holes and the availability of bulk explosives.
- A blast eye device should be placed in the position where the primer will be inserted. This may result in the blast eye alarm sounding prior to charging; however, the alarm will silence once the hole is charged. If emulsion temperature reaches 60°C, the blast eye alarm will sound intermittently. Upon reaching 80°C, the blast eye alarm will sound continuously and the Miner and MMU driver should stop charging the remaining holes.
- Charging is not allowed to start after 11:00.
- No stemming is allowed in holes above 120°C.

- Reloading of MMU is not allowed.
- No sleeping over of explosives allowed.
- Only explosives and stemming vehicles are allowed on the bench.
- All vehicles must be parked in the designated parking area.
- No primary or secondary blasting shall take place with a 15 m horizontal distance from charged holes.

2.1.3.2 Mine D

The holes are charged according to temperature classifications as depicted in Table 12. The charging activity commences with the measurement of the temperature of the holes. Other practices included in the charging procedure are as follows:

- At least three bulk master explosive trucks or two with rapid reload system, must be available (sufficient backup in case of breakdowns).
- All equipment to be used must be safe and in reliable working condition.
- All persons not involved in the blasting operation must be retreated.
- The blasting crew should be briefed to never work over holes.
- Hot holes (red tag) should be charged last without a primer (Table 12).
- Holes should be mid-primed only when the block is ready to be blasted.
- When holes release a brown, yellow and white fumes, workers should be removed, and this indicates rapid oxidation which is a health risk to the workers.
- The use of boosters is not allowed.
- Intersected holes must be indicated with a green flag.
- No sleeping over of explosives will be carried out.

Table 12. Charging procedure for normal and hot holes at Mine D.

	Normal	Cool	Hot Hole
Temperature	-40°C	40 – 60°C	+ 60°C
Stake colour	White	Green	Red
Solid hole	Charge normally	Charge normally	Apply coolant for 1 metre in hole with an airbag on top.
Intersected	Close and re-drill (6.1.3.2. d, e, and f)	Close and re-drill (6.1.3.2. d, e, and f)	Close and re-drill (6.1.3.2. d, e, and f)
Surface	Noisemasters with 12m/s in front line and 75,100 m/s to back	Noisemasters with 12m/s in front line and 75,100 m/s to back	Noisemasters with 12m/s in front line and 75,100 m/s to back
In hole	1m HTD Noisemaster with (200 – 450m/s) delay	1.5m HTD Noisemaster with (200 – 450m/s) delay	1.5m HTD Noisemaster with (200 – 450m/s) delay
Detonator	8D	8D	8D
Booster	400gm	400gm	800gm
Position	10m – 15m down	10m down	Keep on top and drop down when ready to blast.
Stemming	5m chippings	5m chippings	4m – no stemming
Green flag holes	Intersected holes will not be charged	Intersected holes will not be charged	Intersected holes will not be charged
Tie up	Normal	Normal	Normal

2.1.6 SOP Review Summary

A summary of the main findings of the SOP review are shown in Table 13. The findings are categorised under the review themes that include alignment with regulation, identification and the treatment of hot holes.

Table 13. Summary conclusions of SOPs for Mine A, B and C

Theme	Mine A	Mine B	Mine C
Alignment with regulation	<ul style="list-style-type: none"> • The SOP is in alignment with the requirements stipulated in the regulation, however, the definition of hot holes differs. This inaccuracy in the definition does not seem to have an impact on the identification and subsequent treatment of hot holes as prescribed in the SOP. • For all the activities prescribed in the SOP, a competent person is appointed to implement the procedures as required by the regulation. The competent person changes depending on the level of intervention required, e.g., the responsible person may be a blasting assistant, blaster or a drill and blast superintendent. • The measurement of temperatures throughout the length of the hole and with which device is not clearly prescribed in the SOP. The SOP does however indicate that temperatures are recorded before and during charging up activities. 	<ul style="list-style-type: none"> • Hot holes defined as shot holes with temperatures between 40°C and 60°C. • SOP does not consider temperatures greater than 60°C or mention holes that show a temperature increase of 3°C. • A Miner measures hole temperature but SOP does not indicate where measurements are taken throughout on the whole length. 	<ul style="list-style-type: none"> • All personnel involved in blasting operations are expected to be familiar with the relevant provisions of Minerals Act and Regulations, and the exemptions granted under. • Hot Holes are holes with a temperature that exceeds 2°C above the Above Baseline Drill Hole Temperature (ABDHT) of an area. • Any extreme hot hole is any hole with an in-hole recorded temperature of 54°C or above. • All hole temperatures (top, middle and bottom) should be recorded prior to charging. • The Miner is responsible for the destruction of remaining explosives as per the Manage Excess Opencast Explosives procedure. The packs of explosives accessories may be returned to the magazines.

Theme	Mine A	Mine B	Mine C
Identification of hot holes	<ul style="list-style-type: none"> The SOP prescribes a procedure to be followed in identifying hot holes; on a large scale, the mine uses pre-emptive risk assessment to identify areas with potential hot holes. On a day-to-day basis, the identification of hot holes (measurement and classification) is conducted in two days, the preparation day and the day of charging and blasting. Temperatures of all holes on the block are measured, recorded and classified into three different temperature categories (Table 5). In the SOP, it is stated that two independent probes should be used for temperature measurement; there are no specifics given on the type of device (thermocouple, infrared, laser etc...) to be used or how it is used. The blaster is the responsible person in implementing the procedure for identification of hot holes. 	<ul style="list-style-type: none"> On a macro scale, the presence of hot holes is identified by assessing all areas to be mined for spontaneous combustion, particularly in previously mined underground workings. At operational level, hot holes are identified by taking temperature measurements and classifying the holes into categories. However, the measuring method or the temperature measurement instrument is not specified in the SOP. . 	<p>Hot holes</p> <ul style="list-style-type: none"> All hole temperatures (top, middle and bottom) should be recorded prior to charging. Holes with hottest temperature to be recorded prior to charging. Holes identified by Blast Eye Risk Assessment (BERA) Every 3rd hole along the edge of the low wall or the buffer zone. This area is more likely to heat up because it is more exposed to air/venting. The miner will notify the team to remain alert to the blast eye alarm throughout the charging process. Close in quickly due to blast eye alarm. Stop charging immediately if blast eye alarm sounds intermittently. No stemming after blast eye siren sounded. Sleeping over of explosives is only allowed in extraordinary circumstances, these may include equipment breakdown or adverse weather conditions. The closing procedure should be followed.

Theme	Mine A	Mine B	Mine C
			<p>Extreme hot holes</p> <ul style="list-style-type: none"> The Miner will measure and record the temperature of the hot hole on the Drill Hole and Charging Record Sheet prior to blasting. The Miner in conjunction with the Blasting Foreman will review the Mini Risk Assessment to determine the relevant charging procedure to be followed.
Hot hole Bench Preparation	<ul style="list-style-type: none"> The procedure for the preparation of a hot hole bench is similar to that of preparing a normal bench. The detection of noxious gases on the black is of importance as it relates to the issue of venting hot holes. The blaster is responsible for the implementation of activities relating to bench preparation. 	<ul style="list-style-type: none"> The SOP did not explicitly highlight that preparation should be conducted on the same day as blasting however, it is assumed that bench preparation is conducted on the same day as blasting. A safe declaration inspection is conducted by the Miner to declare the blasting area safe. The Miner and the crew must conduct the SLAM risk management process. Areas to be charged are barricaded where the barricade is erected $\geq 15\text{m}$ from the hole that will be charged. Only the MMU and stemming machines are allowed to enter the blasting area while other vehicles park $\geq 15\text{m}$ from holes being charged. 	<ul style="list-style-type: none"> No in-hole detonators for both hot and extreme hot holes. Charging should ensure single day charging. Pre-splitting on overburden is also not allowed. Only two lines of extreme hot holes may be charged. Place guards and barricades to prevent unauthorised access to the hot hole blasting area.
Treatment of hot holes	<ul style="list-style-type: none"> It is prescribed that holes with a temperature above 40°C but less than 80°C are considered for treatment. The hole treatment procedures 	<ul style="list-style-type: none"> Holes with temperatures $>60^{\circ}\text{C}$ should be sealed off. If the hole cannot be sealed off, it should be cooled down 	<ul style="list-style-type: none"> The Miner (and Blasting Assistant) should, based on the temperatures measured,

Theme	Mine A	Mine B	Mine C
	<p>differ according to pre-determined temperatures ranges.</p> <ul style="list-style-type: none"> • Foam expander plugs, gas bags and PVC sleeves are used in the treatment of hot holes of varying temperatures. Temperature measuring and monitoring (blast eye) instruments are used in conjunction with these accessories. • The blaster is responsible for implementing the procedures for the treatment of hot holes. 	<p>with water and a cooling solution e.g., Expectra or instance pyrocool.</p> <ul style="list-style-type: none"> • A second hole is drilled 2m from the initial hole at a depth 2m shorter than the initial hole. • Venting or burning holes (before blasting commences) are sealed off. • A second hole should be drilled at a depth 2m shorter than the initial hole. • The Miner and Blasting Assistant treat hot holes. 	<p>determine if cooling is required. If the temperature is greater than 54°C (60°C minus 10% margin of error), cool hole and repeat temperature measurements.</p> <ul style="list-style-type: none"> • The Miner with Blasting Assistants will insert the blast eye in: <ul style="list-style-type: none"> ○ The hottest hole in the first line to be charged. ○ Two hottest holes not in the first line. ○ Any other hole deemed necessary. • The blast eye should be placed in the position where the primer will be inserted. This may result in the blast eye alarm sounding prior to charging; however, the alarm will silence once the hole is charged. If emulsion temperature reaches 60°C, the blast eye alarm will sound intermittently. Upon reaching 80°C, the blast eye alarm will sound continuously and the Miner and MMU driver will stop charging the remaining holes and tie a blast up for charging.

Theme	Mine A	Mine B	Mine C
			<ul style="list-style-type: none"> The Miner must ensure that all personnel pay attention to any blast alarm sounding.
Charging and blasting of hot holes	<ul style="list-style-type: none"> Charging proceeds according to instructions from the Drill and Blast Mining Engineer. The charging instructions are based on type of area (virgin ground or previously mined), the type of ground (reactive or non-reactive ground) and according to the three hot hole temperature classifications (below 40°C, between 40°C and 55°C and between 55°C and 80°C). 	<ul style="list-style-type: none"> Hot holes are primed with powercord and pentolite boosters. Only emulsion-based explosives are pumped in hot holes. A blast eye is used to monitor emulsion temperature changes. 	<p>Hot holes:</p> <ul style="list-style-type: none"> The Blasting Foreman must ensure that sufficient explosives are arranged The Blasting Foreman must determine the number of MMUs available. The Blasting Foreman must ensure that there is a minimum of two MMUs available. The Miner must determine the number of holes that can be charged based on hole depth and required and available amount of explosives. The priming procedure used at Mine C to prime hot holes states that blast holes should either be top or middle primed. Bottom priming of blast holes is not allowed. The use of in-hole detonators is also not allowed. <p>Extreme hot holes:</p>

Theme	Mine A	Mine B	Mine C
			<ul style="list-style-type: none"> • The Miner/Blasting Assistant will mid-charge holes below 120°C and top prime holes above 120°C according to the initial measurements • To ensure single day charging. • Determine the number of MMUs available for the blast. • Sufficient reload and MMU capacity to be available on the bench prior to the commencement of charging procedure. A minimum of two MMUs is required to ensure consistent supply of bulk explosives during charging. • The miner will determine the number of extreme hot holes that can be charged. • If the blast eye sounds continuously (emulsion temperature of 80°C), the Miner and MMU Driver must stop charging the remainder of the holes. The miner will place the primer in the hole that has been charged and blast as soon as possible. • The Miner with assistance of the MMU Driver will adhere to the following measures:

Theme	Mine A	Mine B	Mine C
			<ul style="list-style-type: none"> ○ Charging should not start after 11:00 ○ No stemming is allowed in holes above 1200C ○ No reloading of MMU allowed ○ No sleeping over of explosives allowed ○ Only explosives and stemming vehicles are allowed on the bench ○ All vehicles must be parked in the designated parking area ○ No primary or secondary blasting shall take place with a 15 m horizontal distance from charged holes

2.2 International standard procedures

In Australia, the Australian Explosives Industry and Safety Group (AEISG) compiled a Code of Practice (COP) guideline for the management of elevated temperatures and reactive ground within the mining industry. The AEISG is composed of Australian explosives manufacturers and suppliers, and it seeks to improve safety and security in the manufacture, handling, transport, storage and use of explosives and related materials. Developing codes of practice is one of the strategies the group uses to achieve this goal (AEISG, 2020). The Code of Practice for elevated temperature and reactive ground covers topics such as regulation requirements, risk assessment, elevated temperature and reactive ground blasting, sampling for reactivity, the selection of explosives product and accessories and training. Although this COP is not an SOP for a specific mine, the contents were found to be valuable when it was reviewed based on the selected review themes.

Alignment with regulation

In the COP, it is stated that the regulatory requirements for blasting in elevated temperature and/or reactive ground differ between the various states in Australia. Additionally, it is stated that the requirements stipulated in the Australian Standard for the storage and use of explosives (AS2187.2 Sections 12.7 and 12.9) are not adequate in detailing how hot holes are identified and treated.

The COP quotes the Australian Standard (2187.2) definition for *elevated temperature* as material that is above 55°C. Materials above 55°C are divided into *hot ground* (ground with material above 55°C but less than 100°C) and high temperature ground (material with a temperature of 100°C or more). The Australian regulation, as quoted in the COP, stipulates that the temperature of holes should be measured 2 hours after drilling has occurred, whereas the temperature of breakthrough holes should be measured 4 hours after these holes are sealed. The temperature should be measured along the length of the hole and the highest temperature measured should be recorded as the temperature for that hole (AEISG, 2020). Using the available information on hole temperatures, the AEISG (2020) recommends the zoning of a block according to temperature bands. In the COP, it is also noted that the temperature of the hole may vary over time and thus, temperature measurements should be repeated to illustrate trends that may be useful in determining the sleep time.

Identification of hot holes

The AEISG (2020) recommends the development of mine-specific SOPs for measuring and monitoring hole temperatures that would be used if there is any risk of hot holes (elevated temperature). In the COP, the group recommends the adoption of a proactive strategy that involves determining the cause of the elevated temperatures and analysing the history and location of hot holes across the mine. The AEISG (2020) recommends the following as procedures that should be contained in an SOP for the identification of hot holes by temperature measurement:

- How to identify which holes to test, and when, and how often to test (e.g., test every hole, test every hole in a certain known hot area, test 24 hours apart to check for increasing temp).
- What equipment is to be used to test (e.g., for initial checks, final checks).
- What procedure is to be used for testing, including the calibration of equipment.
- Site temperature cut-offs (e.g., 55°C, 70°C).
- Record keeping procedures.
- How to act on the information, including reporting procedures, retesting, backfilling etc.
- How elevated temperature holes are to be marked (AEISG, 2020).

Instruments such as thermocouples, infra-red guns and infrared cameras are some of the temperature measurement and monitoring instruments assessed in the COP. The AEISG (2020) recommends the use of in-hole temperature measurement instruments that have functionalities for producing a profile of hole temperatures along its depth. Such a profile is useful since the highest hole temperature may not always be at the bottom of the hole but anywhere along the depth of the hole (AEISG, 2020). In addition, the group recommends that risk assessments should be updated continuously to include changes such as the replacement of an old model with a new temperature measurement instrument model.

Hot hole bench preparation

A site emergency plan should be in place detailing the evacuation of the area and incident reporting to senior site officials, the explosives provider and the relevant state authorities.

Treatment of hot holes

The risk management process should identify holes with temperatures in excess of the allowable loading temperature, so that they can be left uncharged or backfilled. The key principles for effective temperature logging include:

- Selection of a measurement device with a suitable temperature range and a measuring system suitable to the conditions (e.g., infra-red may not be effective in wet holes or steaming holes).
- Hole-by-hole logging.
- Recording maximum hole temperature.
- Frequency of measurement.
- Recommendations on how to act on the temperature information.

Charging and blasting

The AEISG (2020) notes that hot ground affects the different types of explosives products (bulk and packaged) and accessories such as initiation systems over time by increasing the rate of degradation which may lead to potential failure and the subsequent misfiring and premature detonation. The COP recommends the demarcation of areas into elevated and non-elevated temperature zones, which enables a mine to select zone-specific explosives products and the associated sleep times. The sleep time in hot holes should

be minimised to prevent the heating up of explosives products which may result in premature detonations (AEISG, 2020).

The AEISG (2020) advises that, for those holes that are charged, a hole charging sequence should ensure that loading occurs near the initiation point first to allow the pattern to be quickly tied up and fired in the event of a change in the risk or conditions of a block. Where it is deemed practical, the hottest holes on a block should be loaded last (AEISG, 2020).

Other recommended practices for charging and blasting in hot hole environments include the following (AEISG, 2020):

- Accessory selection - Initiating explosives used in elevated temperature and/or reactive ground conditions should be compatible with the high explosives they are to be used with and the environment in which they are to be used. Relevant technical data sheets are consulted, and the suitability of the initiating explosives discussed with the supplier.
- Misfires in elevated ground - Site specific misfire procedures should be in place detailing the hazards associated with elevated temperature ground.
- Extending sleep time - Risk assessment procedures should be in place to manage the case of a misfire not being able to be removed within the authorised sleep time of the product.

The International Energy Agency recommends that heating coal piles should be monitored by measuring temperatures using thermocouples. Additionally, infrared and light sensitive ultra-violet monitors may also be used as they provide images that assist in identifying areas of elevated temperatures (Sloss, 2015).

3 Protocol for experimentation

Various tests on the different hot hole management accessories had to be conducted at the experimentation site. The tests would assist in determining a standard methodology that can be used by various mines to ascertain the suitability of these accessories. Different protocols for the various hot hole management accessories were designed with the assistance of Mine A personnel, who have previously performed similar tests at their operation. It should be noted that due to the different mining conditions, the protocols can be adapted by the user to accommodate factors that were not considered in these baseline versions of the protocols. Furthermore, there are various products with vast technological innovations, therefore, the protocol may be limited to aspects of already existing products or those that will be available for testing. However, the designed protocols that are described in the following sections, consider the main safety and production aspects and can be used to produce in-depth protocols for new or improved products in the future.

3.1. Protocol for testing of temperature measurement and monitoring devices

3.1.1. Objective

This protocol details the method followed in evaluating different temperature monitoring instruments in a hot hole mining environment. The protocol aims to provide an understanding of temperature change in hot holes over time. This information is crucial in the development of procedures necessary to improve safety and productivity in a mining operation with hot holes.

3.1.2. Application of the protocol

This protocol is applicable to the testing of thermocouples and infrared temperature monitoring and/or measuring instruments:

- With preferably, a temperature range of 0°C to 300°C
- That work in environments with dust, smoke, and water.
- That certify mining legislation for use in hot operations.

3.1.3. Benefits of the protocol

This is a simple on-field protocol performed in realistic and harsh mining conditions with heat, dust, fumes or smoke and water. The protocol covers the safety aspects related to mining in hot hole environments. Additionally, productivity aspects such as the duration to measure the temperature of each hot hole can also be investigated using this protocol. This provides a balanced method for selecting the optimal temperature monitoring instrument. Testing under a real mining production environment was preferred to lab testing of the temperature monitoring instruments, that may provide inaccurate and misleading results.

3.1.4. Limitations of the protocol

Mining conditions vary between different sites and even within a single block. It is therefore difficult to have the same test conditions from hole to hole. However, the results from the

use of this protocol have provided a more in-depth insight into hot holes compared to repeatable lab tests. Another limitation of the protocol is that the optimal number of data samples required to produce extensive data is not well-defined. Since this is a new field of research, it is anticipated that future versions of the protocol will provide more specific sample size requirements and other test specifications.

3.1.5. Tools and materials used

The following tools and materials are required for this protocol:

- Temperature monitoring device (and accessories).
- Measuring tape.
- Stopwatch.
- Camera.
- Note pad.
- Drill/Blast holes with temperatures exceeding 40°C.

3.1.6. Procedure

This section describes the steps to be followed (Figure 32) in implementing this protocol.

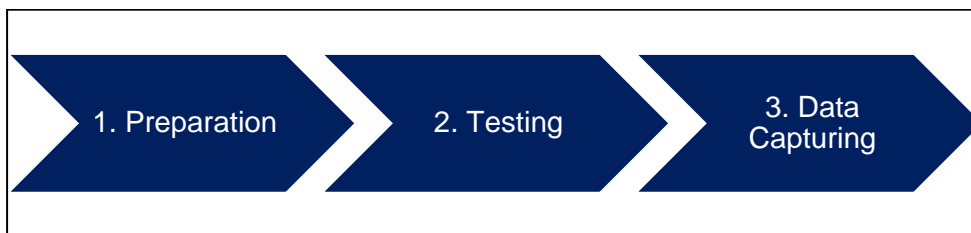


Figure 32. Steps for testing of temperature measurement and monitoring devices

1. Preparation

- Set up the instrument as per the manufacturer specifications.
- Test for the presence of water in the blasthole by any safe method, e.g., dropping a weight and listening for the sound made when the weight hits the water or immersing a dry material, retrieving it and inspecting for wetness (care should be taken as the material may be hot).
- Calibrate the temperature monitoring/measuring device before use.
- Measure hole depth.

2. Testing

- Lower the cord of the measuring instrument into the blasthole (avoid bumping the instrument on the walls of the blasthole).
- If the instrument is in the form of a “gun”, point the instrument to the spot in the hole to be measured.
- Follow the manufacturer specifications on how to take a reading.
- Pull out the cord/cable out of the hole carefully to avoid damaging the instrument.

- Take pictures of temperature measuring process.

3. Data Capturing

- Capture the data (temperature, depth, pressure etc.) as per manufacturer specifications.
- Ensure that the data is documented or saved before proceeding to the next hole.

3.1.7. Acceptance Criteria

The criteria for evaluating the temperature measuring and monitoring devices are described in Table 14.

Table 14: Acceptance criteria for temperature measuring or monitoring devices

Criteria	Definition
Accuracy	The accuracy of temperature readings relative to a standard calibrated instrument.
Response time	The time it takes for a probe/sensor to make a measurement and display it on the output device (screen/alarm light).
Temperature Range	The range of temperatures at which the instrument functions without failure. (In the preliminary temperature measuring tests, temperatures of up to 500°C were measured at a coal mine).
Length of temperature measuring wire, cable, or string	The length of the wire/string/cable or any part of the instrument to be immersed into the hot hole.
Durability of the wire, string, cable or the device or probe	This is a qualitative criterion to assess the visible damage suffered by the wire, string, cable or the device or probe during temperature measurement/monitoring.
Instrument set up time	The time it takes to set up the device and its accessories before a temperature measurement can be made in a hot hole.
Position of temperature measurement in the hole (single or multiple point)	This refers to the temperature profile of the hole. A device can either produce a profile of temperatures along the depth of the hole due to multiple sensors or probes or produce a single temperature reading at one point in the hole.
Visibility of temperature readings and warning lights	The display of the control system output (monitor, LCD screen, LEDs, lights etc.) temperature readings visibly in different environmental conditions (sunlight, rain, darkness, dust etc.).
Audibility of warning/alarm system	This refers to whether the warning or alarm system of the device can be heard clearly on a bench.
Time taken to take a reading per hole	This refers to the duration required to immerse the wire, string, cable or probe into the hole to the required depth, take a reading and retract it from the hot hole.

3.2. Testing of gas bags

3.2.1. Objective

This protocol details the method followed in evaluating different gas bags in a hot hole mining environment. The protocol aims to assess the effect of temperature on the functionality of gas bags in hot holes. This will enable mines to decide on how to use gas bags optimally in hot holes and avoid safety incidents.

3.2.2. Application of the protocol

This protocol is applicable to the testing of gas bags (or air bags or blast bags) that are used to seal off hot holes. The protocol also caters for the use of gas bags in holes that breakthrough to underground workings; in these cases, the bags are used to provide a platform for loading explosives.

3.2.3. Benefits of the protocol

The protocol is for a simple in-field test to be performed in realistic hot hole environments. Actual hot holes are used, thus, providing a rugged surface that may not be available for lab tests. The protocol adheres to safety practices in hot hole environments.

3.2.4. Limitations of the protocol

In addition to varying geological conditions, environmental conditions such as the ambient temperature and atmospheric pressure and hole conditions that include the presence of water or fumes may affect the results of the tests. In addition, the same conditions are difficult to replicate from hole to hole. However, the protocol provides a method for a test in an actual hot hole, which is invaluable for the safety and health of personnel. Another limitation of the protocol is that the optimal number of data samples required to produce extensive results is not well-defined. Since this is a new field of research, it is anticipated that future versions of the protocol will provide more specific sample size requirements.

3.2.5. Tools and materials used

The tools required for the test are:

- A temperature measuring device (3 standard K-type thermocouples were used).
- A tape measure.
- A gas bag.
- A stopwatch.
- A camera.

3.2.6. Procedure

The set-up for testing a gas bag in a hot hole is shown in Figure 33. Three thermocouples are inserted in the hole with, one below the hole, one between the wall of the hole and the gas bag and the other above the gas bag. Similarly, a device with multiple sensors can be used, ensuring that there are sensors below, on the bag and above the bag. Temperature

readings are then taken at specific time intervals, for example, every two, five or ten minutes, while inspecting the condition of the bag.

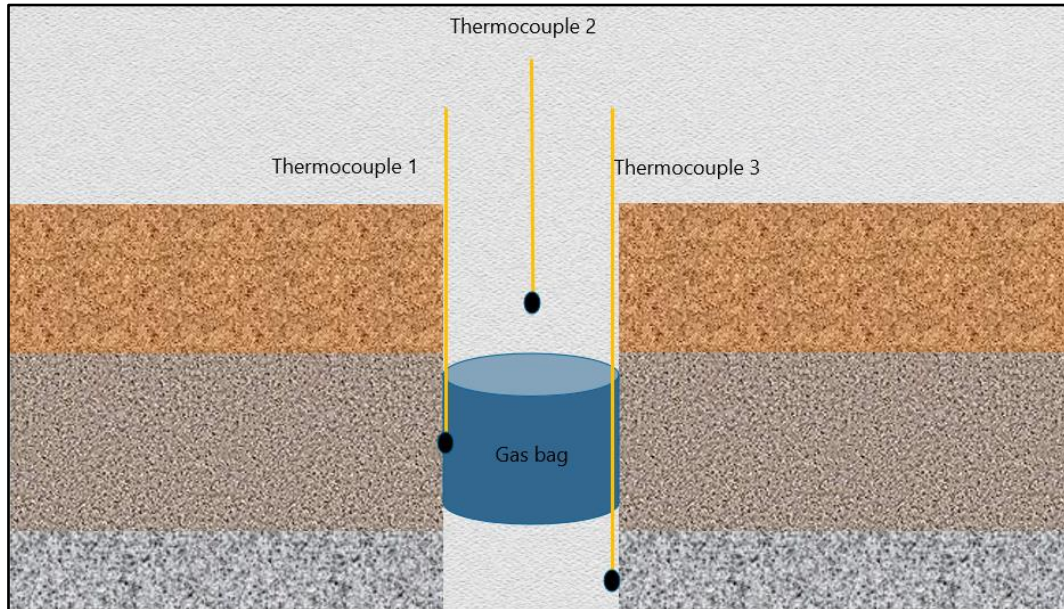


Figure 33. The set up for testing a gas bag in a hot hole

The state of the bag, (inflated or deflated), was monitored by slightly pulling the thermocouples 1 and 2 upwards. Once the bag was inflated, it was pressed against the wall of the hole and would not allow for pulling of the thermocouples upwards. Additionally, a stone was thrown regularly on to the gas bag in the hole; the sound made by the stone bouncing (or not) on the gas bag was used to indicate whether the bag was inflated or deflated.

3.2.7. Acceptance Criteria

- Temperature range.
- Duration at temperature range.
- Confined and unconfined pressure.

3.3. Testing of foam expander bags or plugs

3.3.1. Objective

This protocol details the method followed in evaluating expanding foam bags or plugs in a hot hole mining environment. The protocol aims to assess the effect of temperature on the functionality of foam bags or plugs in hot holes. This will enable mines to decide on how to use expanding foam bags optimally in hot holes, thereby avoiding safety incidents.

3.3.2. Application of the protocol

This protocol is applicable to the testing of expanding foam bags that are used to seal off hot holes. The protocol also caters for testing of expanding foam bags in holes that breakthrough to underground workings to determine whether they can be used to provide a platform for loading explosives.

3.3.3. Benefits of the protocol

The protocol is for a simple on-field test to be performed in realistic hot hole environments. Actual hot holes are used thus, providing a rugged surface that may not be available in lab tests. The protocol adheres to safety practices in hot hole environments.

3.3.4. Limitations of the protocol

The varying geological conditions within a mine, a block and within a hole, for example, the presence of fumes and different locations for sources of heat, may affect the results of the tests. However, the value of the protocol is that it provides a method for a test in an actual hot hole, which is invaluable for identifying safety and health aspects that may be omitted in lab tests. Another limitation of the protocol is that the optimal number of data samples required to produce extensive results is not well-defined. Since this is a new field of research, it is anticipated that future versions of the protocol will provide more specific sample size requirements. Lastly, the position of the foam bag in the hole is critical to determining the expansion length; the tests results may be affected by inaccurate depth measurements.

3.3.5. Tools and materials used

The tools required for the test are:

- A temperature measuring device(s) (2 standard K-type thermocouples were used).
- A tape measure.
- An expanding foam bag.
- A stopwatch.
- A camera.

3.3.6. Procedure

The set up for testing an expanding foam bag in a hot hole is shown in Figure 34. Two thermocouples are inserted in the hole, one below the foam bag and the other above the foam bag. In this way, only one thermocouple is partly destroyed on retrieval. Alternatively, a third thermocouple can be placed between the wall of the hole and the foam bag, although this thermocouple would not be recovered for future use. The other alternative to the set up could be the use of a multiple sensor device, ensuring that there are sensors below, on the bag and above the bag. This device, however, will be destroyed on retrieval due to the permanent sealing nature of the foam bag.

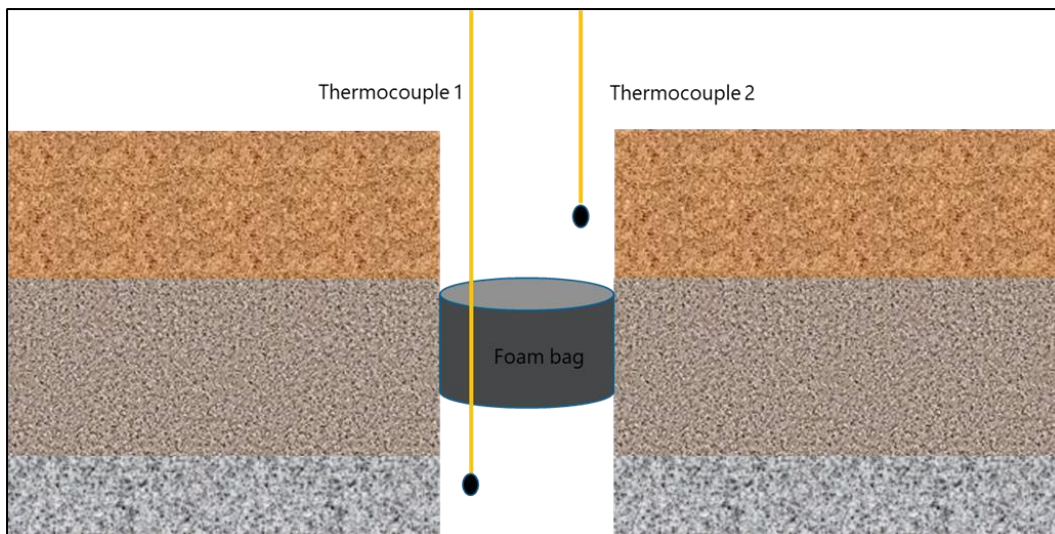


Figure 34. The set up for testing an expanding foam bag in a hot hole

It is expected that the device will expand upwards, based on the manufacturer instructions for inserting it in a hole. Therefore, the change in height of the foam bag (expansion length) was measured within 2 minutes of inserting it into the hole using a tape measure. The temperature is monitored through the test using the two thermocouples. In summary the steps are as follows:

1. Measure the hole depth.
2. Insert thermocouple 1 at a known depth and take a temperature reading.
3. Insert expanding foam bag as per manufacturer instructions at known depth (alternatively a third thermocouple could be inserted together with the foam bag).
4. Insert thermocouple 2 at known depth and take initial temperature reading.
5. Measure the new depth after foam bag has expanded.
6. Measure temperatures at specific time intervals.

3.3.7. Acceptance Criteria

The following criteria were used to evaluate the performance of the foam bags in the hole:

- Expansion height of the foam bag.
- Temperature changes below and above the foam bag.
- Flammability of the foam bag.

3.4. Testing of sleeves

3.4.1. Objective

This protocol details the method followed in evaluating PVC or plastic sleeves in a hot hole mining environment. The protocol aims to assess the impact of sleeves in providing insulation to an explosive product (emulsion) that is loaded into a hole. This is important in determining whether hot holes of varying temperatures can be loaded with explosives

and blasted within a particular period on the bench, safely and without the high temperature interfering with the performance of the product. In this way, a mine would be able to determine the temperature limits at which to charge holes and the safe period that may be spent on a bench with charged hot holes before blasting.

3.4.2. Application of the protocol

This protocol is applicable to the testing of plastic and PVC that are used to provide insulation in holes charged with explosives products such as emulsion. Further tests that may be included in this protocol would be testing the strength of the sleeves for containing explosives in holes that have been drilled through to underground working.

3.4.3. Benefits of the protocol

The protocol is for a simple in-field test to be performed in realistic hot hole environments. Actual hot holes and explosives products are used thus, providing a real test environment that may not be available in lab tests. The protocol adheres to safety practices in hot hole environments.

3.4.4. Limitations of the protocol

The varying geological conditions within a mine, a block and within a hole, for example, the presence of fumes and different location for sources of heat, may affect the results of the tests. However, the value of the protocol is that it provides a method for a test in an actual hot hole, which is invaluable for identifying safety and health aspects that may be omitted in lab tests. Another limitation of the protocol is that the optimal number of data samples required to produce extensive results is not well-defined. Since this is a new field of research, it is anticipated that future versions of the protocol will provide more specific sample size requirements.

3.4.5. Tools and materials used

The tools required for the test are:

- A temperature measuring device(s) (2 standard K-type thermocouples were used).
- A tape-measure.
- A PVC sleeve of correct length and diameter.
- A stopwatch.
- A camera.

3.4.6. Procedure

The set up that was used for testing a sleeve is depicted in Figure 35. Two thermocouples are inserted in the hole; one thermocouple is placed outside the sleeve (between the sleeve and hole wall) and the other thermocouple is placed inside the sleeve as explosives are loaded into the hole. For the tests that were conducted, a multiple blast eye device, was inserted simultaneously with thermocouple 1 to monitor any temperature variation in the explosives product. The device sounds an alarm when in-hole temperatures exceed a

set benchmark. Alternatively, a multiple sensor temperature measuring device would be used in the place of the thermocouples.

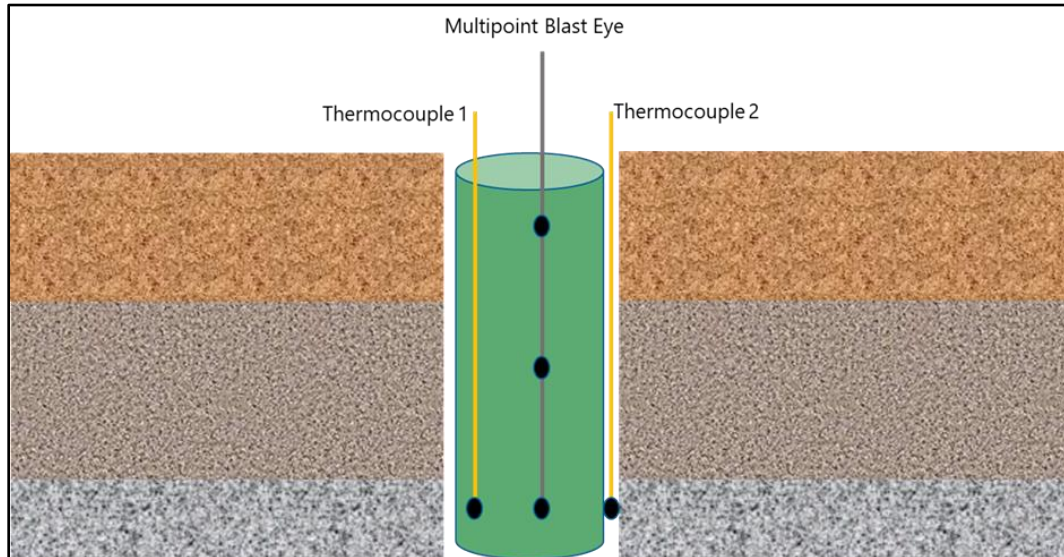


Figure 35. The set up for testing a sleeve in a hot hole

Once the set-up is complete, temperature measurements should be taken at specific time intervals. For the tests that were conducted, the Multiple Blast Eye device, was simultaneously monitored for alarm sounds and the associated flashing of the alarm lights.

3.4.7. Acceptance Criteria

The following criteria were used to evaluate the performance of the sleeves in the hole

- Temperature difference between the two thermocouples to determine whether any insulation is provided.
- Temperature change in the explosives product based on the warning alarm system of the Multiple Blast Eye device.

4 Assessment of current hot hole management practices

The researchers conducted on-block observations for four weeks at Mine A and one week at Mine B. The purpose for this was to assess the practical application of the mine's current hot hole management practices as stipulated in the SOP and understand the evolution of hole temperatures from drilling to ignition on the production block. It should be noted that at Mine A, during the duration of the project, some continuous improvements and innovations were made on hot hole procedures, such as the piloting of a multi-point blast eye to monitor the in-hole emulsion temperature throughout the depth of the hole. Therefore, these observations were based on the version of the procedures at that time.

4.1 Mine A

Mine A is an open cast coal mine located on virgin ground and on previously mined underground workings. The prevalence of hot holes was found to be associated with those blocks located above old underground workings. The research team observed the use of blast accessories and temperature monitoring instruments and how these are consistently used by the different shifts. These blast accessories include foam expander plugs, PVC sleeves and gas bags. Temperature measurements were taken using a K-Type thermocouple and an infrared device, the Insight Blasthole Temperature Logger. The monitoring of emulsion post charging was conducted using the Blast Eye device from African Explosives Limited (AEL). The following observations were made:

Drilling Team

- The drilling team is responsible for drilling of holes, clearing the collar and capturing information about the hole on white tags. This information includes the hole number (based on the drill pattern), the planned and actual depths and any other information that may be useful to the blasting team.
- The team is responsible for closing the holes with plastic cones to prevent the ingress of water and drill chippings.
- The drilling team does not capture information on in-hole temperature or hole conditions such as venting, however, when venting holes are encountered after drilling, these are sealed off at the collar using gas bags or foam bags.

Blasting Team

- The blasting team is responsible for calibrating both the temperature measurement devices daily using water (for the K-Type thermocouple) and a calibrator for the infrared device.
- A safety meeting is held at the offices, before the team leaves for the mining blocks, to discuss various safety issues and the plan for the day.
- A safety talk is held on the block before work commenced to alert the team members on the likely safety hazards on block that day and the precautionary measures to be followed.
- On the preparation day (the day preceding the day of charging), in-hole air temperatures were measured using the K-Type thermocouple and the in-hole rock

temperature was taken using the infrared device. These temperatures are written on a tag that has a colour corresponding to the temperature classification found in the SOP. The tags are placed at the hole collar of the hole as shown in Figure 36 where there are red tags (indicating a temperature greater than 55 °C), white tags (containing hole information that includes the temperature) and a blue tag (indicating that it is a pillar hole). The temperatures are also captured on a data sheet to be submitted to the mining engineering department who will then plan a blast based on the highest temperature measured on the block.



Figure 36: Drill holes with red tags (>55°C) and white tags with hole information captured

- Three people were responsible for using the infrared device; one holds the output display system (the logger), the other team member is responsible for inserting the cable and probe into and out of hole. The third team member captures the temperature readings on a tag. The overall maximum in-hole rock temperature and the maximum in-hole temperature at the bottom of the hole were recorded. Water is used to cool off the probe before proceeding to the next drill hole.
- Two people are responsible for taking measurements using the K-Type thermocouple. One team member holds the digital thermometer and inserts the temperature wire into the hole, while observing the temperature change. The in-hole air temperature at the bottom of the hole and the maximum in-hole air temperature are recorded on a tag and the data sheet by the other team member. When measuring hole temperatures using the K-Type thermocouple, blasting assistants took approximately 2 minutes or less to take readings in each hole.
- On the charging day, accessories such as PVC sleeves, gas bags, expander foam plugs, and monitoring devices are brought to the bench.
- For venting holes, PVC sleeves were inserted in the hole before charging. Plastic sleeves were initially used for non-venting holes; however, this practice was later discarded when a reactive ground explosive was made available by the explosives supplier. The PVC sleeves are used to carry the explosives to avoid direct contact between the surrounding rock (which is of high temperature and may cause

spontaneous detonation) and the explosives (emulsion). Figure 37 shows PVC sleeves placed next to the recipient holes just before charging commenced.



Figure 37: Sleeves placed next to hot holes before charging (circled in red)

- There were some inconsistencies observed regarding the sealing of holes. According to the SOP, those hot holes with a temperature that exceeds 80°C should be sealed off with foam expander plugs. However, on-field observations showed that holes up to 99°C were charged (and thus not sealed off); rather, those holes that were sealed off had temperatures exceeding 100°C. The misalignment (as explained by the technical personnel at the mine) was due to the lag between the adoption (and sign off) of new procedures and implementing these procedures on the ground. The new set of procedures, which were updated in July 2021, allows for the charging of holes up to 100°C with the use of PVC sleeves. Figure 38 shows a hole that was sealed at the collar using an expanding foam plug.



Figure 38: Foam expander plug used to close off a hot hole

- AEL Blast Eye devices were inserted in those holes in which sleeves were used during charging.
- Figure 39 shows a hot hole that had a flame at the bottom. This hole was not charged and blasted due to the presence of flames and high temperature readings in excess of 500°C before a thermocouple reached the bottom. The hole was sealed off using expanding foam.



Figure 39: Fire observed in a hot hole on a block at Mine A

4.2 Mine B

Mine B is an opencast strip mine. Opencast strip mining currently occurs above old underground workings. It has been classified as a hot hole mine and therefore does not make use of detonators.

The following was observed during the on-block observations:

- A safety meeting was held on the block before work commenced. This was to conduct a Stop, Look, Assess and Manage (SLAM) assessment for safety hazards to look out for.
- The night shift drilling team closed off all venting holes with a cone. Thereafter, a new hole was drilled 2 m away from the initial hole and 2 m shorter (in length). This serves as an initial step in managing hot holes.
- The average hole depth across benches was 26 m.
- The UNI-IT handheld infrared device was used to measure hole temperatures. This instrument is held like a gun and pointed in the hole where a laser is released, and temperature is measured.
- Hole temperatures were taken at the bottom of the hole.
- Hole temperatures were measured only before charging of holes.
- Holes that were observed to have temperatures less than 40°C therefore the research team was not exposed to several hot holes on benches.
- Hole temperature readings varied between 17°C and 37°C.
- One bench had two venting holes at temperatures of 52°C and 70°C which were not charged but sealed off during the blast.
- Water in wet holes was removed during the charging process. Since water is less dense than the explosives product, it flowed to the top of the hole and was eventually removed from the holes as the explosives product was filled.
- Holes were stemmed to 6 m using drill chippings.
- Benches had varying hole sizes due to the use of different drilling machines (Figure 40).
- The blast eye device was inserted on the first row on the bench and the first hole. The majority of the holes had temperatures less than 40°C but the device was used nevertheless, to monitor possible temperature increases.
- The blasting team does not cool down hot holes but manage them through closing them off using a cone or leaving them uncharged. This is contrary to the SOP which states that hot holes with a temperature greater than 60°C are cooled with water and a cooling solution.



Figure 40: Drilled and charged holes of inter-burden middle seam before a blast.

5 Experimentation at test site and production blocks

The performance of various hot hole management accessories including temperature monitoring instruments was investigated at two test sites located at Mine A. At Test Site 1 (Figure 41a), the holes were drilled on virgin ground whereas at Test Site 2 (Figure 41b), the holes were drilled on previously mined underground workings. Most conditions on both sites were similar, for example, there were wet and dry holes, venting and non-venting holes and holes of different depths. Some of the conditions are depicted in Figure 41. The hottest holes, with in-hole air temperatures of more than 300°C, however, were found at Test Site 2. Some of these holes were *bhoboza* holes.



(a)



(b)

Figure 41. Conditions at the two test sites

Hot hole management accessories such as gas bags, expanding foam plugs and PVC sleeves from different manufacturers were tested depending on their availability. This was done to identify those accessories that may be useful in managing the safety risks associated with hot hole environments. Other experiments included investigating the change in temperature and other visible conditions of hot holes over time. Understanding the behaviour of holes in hot environments is important in determining when and how a blast should be executed and what procedures and accessories should be used.

Fundamental to all the tests was the process of temperature measurement. Measurements were taken using the available instruments thus, the temperatures were limited to in-hole air temperature and to a lesser extent, in-hole rock temperature measurements. A K-Type thermocouple and a digital thermometer were used for the majority of the tests due to their high availability, simplicity and affordability. As described in Section 3, in some of the experiments, the measuring device was either destroyed during the experiment or could not be retrieved from the hot holes. Therefore, the K-Type thermocouple was convenient and fit for this purpose, unlike other instruments such as the infrared device which would be expensive to replace after being destroyed in the hot holes. An infrared temperature measurement device was used to detect the in-hole rock temperature. Due to the sensitivity of the device to high temperature and its high cost of replacement, it was not used in holes with temperatures exceeding 150°C. Other in-hole air temperature measurement devices were used for specific tests. In addition to the temperature

measurements carried out pre-blasting, it is important to understand the change in temperature in the holes after charging with explosives products. Thus, the performance of devices designed for this purpose was assessed. These devices are designed to alert mine workers of rising in-hole explosives product (emulsion) temperatures from the start of charging until prior to the setting off of a blast. These experiments however were limited due to the safety risks and regulations associated with handling explosives and the availability of the devices.

Similar tests to those conducted at the test sites were carried out at production or mining blocks at Mine A. Similar conditions such as venting were found at the mining blocks. The major difference between the test sites and the mining blocks was that there were freshly drilled holes at the mining blocks compared to the older holes found at both test sites. Moreover, the production blocks presented the researchers with an opportunity to experience the daily hot hole management procedures practiced at the mine. At the mining blocks, time was a major limiting factor as anticipated, due to safety regulations and procedures that prevent excess personnel on mining blocks and the handling of explosives by personnel other than those appointed.

Baseline Conditions at Test Site 1

At Test Site 1, experiments were conducted for a duration of four weeks on 52 holes. The tests followed the protocols described in Section 3 of the report. However, since these tests are a new field, adaptations were made, during the testing period, to the protocols to improve the quality of the outcomes. Baseline temperatures and depths were measured in all the holes and documented. In line with the mine standards at Mine A, tags of different colours (Figure 41) were used to mark the temperature and depth of the holes as follows:

- White tags – used to mark holes with temperatures less than or equal to 40 °C.
- Yellow tags – used to mark holes with temperatures between 40 °C and 54 °C.
- Red tags - used to mark holes with temperatures ≥ 55 °C.

More than half of the holes at the test site were shallow, with depths of less than 10 m. This is due to the holes getting blocked with debris over time and in some cases, it was suspected that the holes were blocked with gas bags or other hot hole accessories trialled at the test site in the past. It is noteworthy that, the conditions of the holes may have influenced the results and therefore, may not necessarily reflect the behaviour of production holes (with greater depths) on actual mining blocks. Figure 42 shows the variation in the hole depths at Test Site 1.

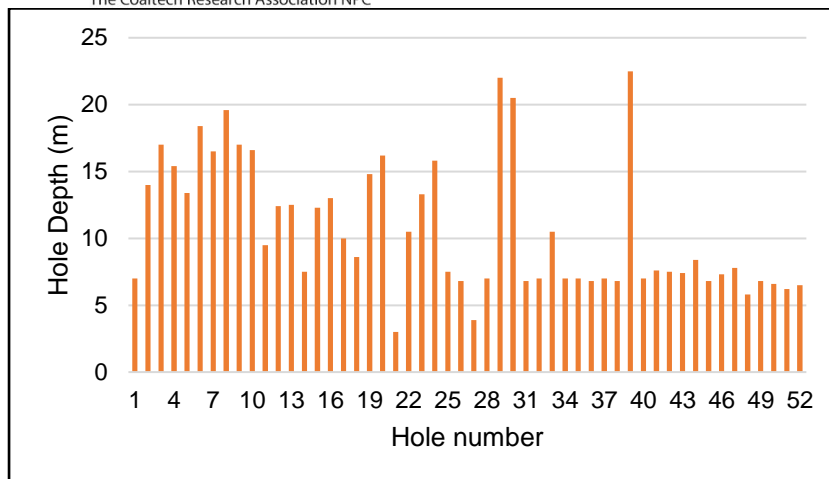


Figure 42. Variation in hole depths at Test Site 1

Baseline Conditions at Test Site 2

Additional experiments were carried out at Test Site 2, a location adjacent to Test Site 1 but, drilled over old underground workings. The holes at this test site were generally deeper (close to 30 m) than those holes at Test Site 1 as depicted in Figure 43. The depth of some of the holes is not shown as they holed out to underground workings (bhoboza holes), but they also had depths of greater than 30 m. The temperature measurements at Test Site 2 were somewhat limited by the unavailability of durable temperature measuring devices that could accurately read high temperatures repeatedly.

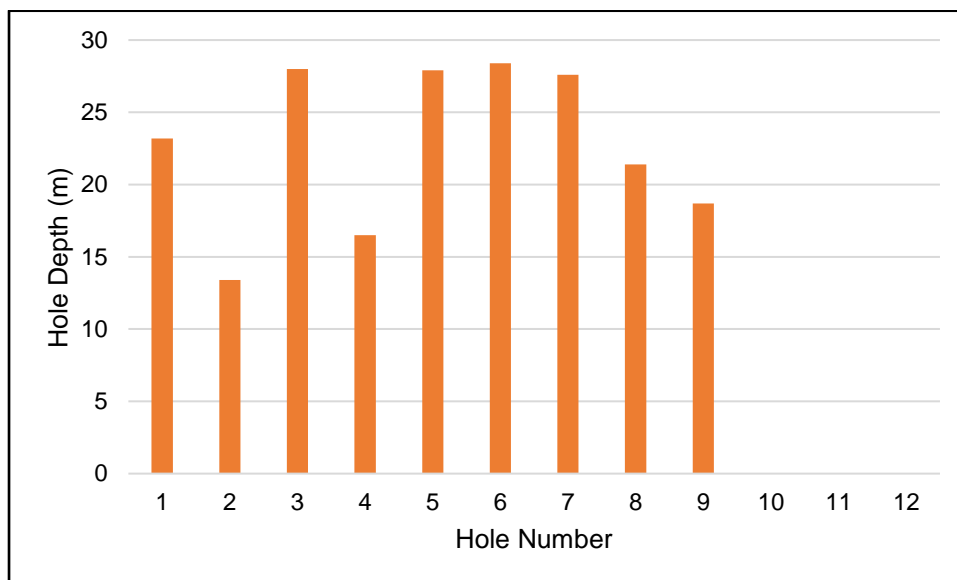


Figure 43. Variation in hole depths at Test Site 2

5.1 Evaluation of temperature measurement and monitoring devices

Temperature measurement and temperature monitoring devices were tested at both the test sites and at mining blocks. As discussed in Milestone 2 of the project and for purposes of this milestone, temperature measurement devices refer to those devices that detect either the air or rock temperature reading. These devices are normally used from the time holes are drilled until prior to charging. All the temperature measurement devices that were

tested detect the temperature within the hole. In contrast, temperature monitoring devices are used to give an indication of a rise in the temperature of pumpable explosives. They are designed with alarm functionality to alert workers when a specific “unsafe” temperature is reached, after which safety procedures such as clearing the block are then implemented. Some devices, however, are designed to perform both the temperature measurement and monitoring functions from drilling until prior to blasting.

An infrared temperature measurement device, which measures the in-hole rock temperature and various thermocouples, that measure the in-hole air temperature were tested (Figure 44).



Figure 44. Temperature measurement devices

The criteria used to test these devices are described in Section 3.17 of this report. The criteria include technical device specific factors such as temperature range and durability and some operational (and subjective) factors such as the duration it takes for a measurement to be taken per hole.

Time studies were conducted to determine the time it takes for a temperature measurement to be taken using the K-Type thermocouple 1, the Temperature Log device, the Blast Hole Temperature Logger and the Hot Hole Management System (HHMS). The HHMS was included in the temperature measurement time studies because of its dual functionality of temperature measurement and temperature monitoring. The second K-Type thermocouple was excluded from the time studies due to technical malfunctions and the erroneous temperature readings as a result of the metal casing that encloses the temperature detecting probe. These issues are discussed further in Table 15. Further information on the tests on temperature measurement and monitoring devices are found in Appendix A – Tests on temperature measurement and monitoring **devices**). Figure 45 shows the results from the time studies conducted by the research team.

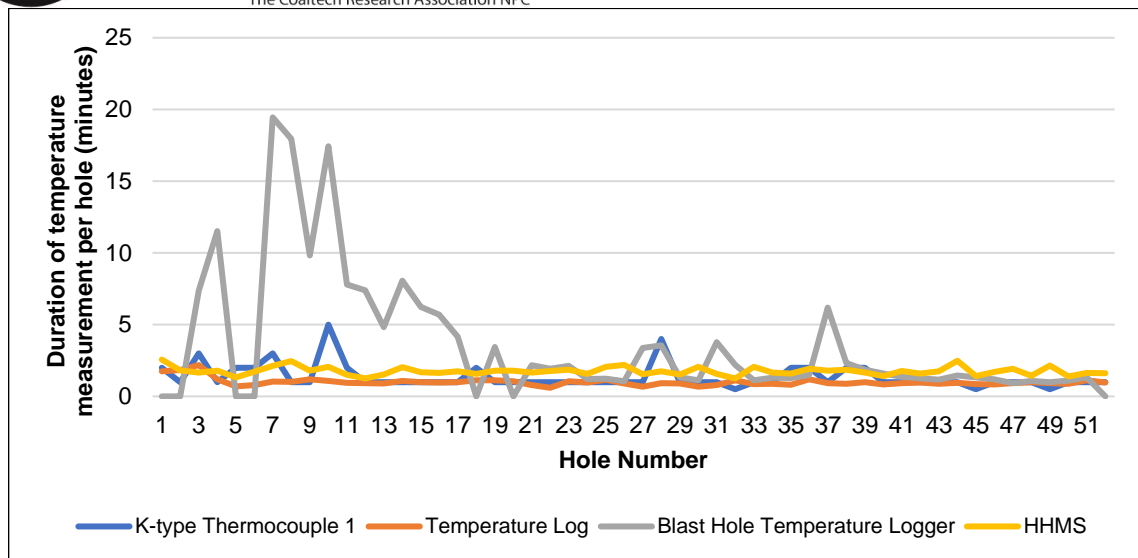


Figure 45. Time study on temperature measurement per hole for various devices

The longest time to measure a hole at Test Site 1 was taken when using the Blast Hole Temperature Logger, an infrared device. The average duration of temperature measurement per hole for this device was calculated to be 3.5 minutes. It is noteworthy that between Hole Number 1 and Hole Number 17, the time taken per measurement was considerably high due to the researchers familiarising themselves with the functionality of the device. Thus, this had an influence on the average duration of measurement per hole. The Blast Hole Temperature Logger requires the inputting of data such as the site or location and the hole ID before the cable is released into the hole. This takes about 30 s. The rest of the time is consumed in releasing the cable down the hole and retrieving it from the hole. The time taken to measure a hole by the remaining three devices averaged below 2 minutes. In some instances, the K-Type thermocouple wire would entangle resulting in minor delays. These are shown in Figure 45 as peaks on the K-Type Thermocouple graph. Similar entanglements of the temperature wire were experienced with the HHMS resulting in minor delays. Bluetooth connection issues were experienced with the Temperature Log device, which uses a Bluetooth connection and a mobile phone to log the temperatures. These issues resulted in minor delays in the temperature measurement process.

In addition to the time studies, the devices were assessed according to the criteria detailed in the protocol for experimentation (Section 3.1). Table 15 and Table 16 are summaries of the assessment of temperature measurement and temperature monitoring devices respectively.

Table 15. An evaluation of temperature measurement devices

Criteria	K-Type Thermocouple (Sinometer)	K-Type Thermocouple (Fluke)	Temperature Log (QMR)	Blast Hole Temperature Logger (Insight Technical Support)
Accuracy	<ul style="list-style-type: none"> The device produces accurate temperature readings when used correctly and when there are no faults on the wire or on the multimeter. These temperature readings can be confirmed by calibration and when compared with an in-hole rock temperature measurement device. 	<ul style="list-style-type: none"> In reference to other calibrated temperature measurement devices, the temperature readings are inaccurate and lower by up to 20°C. This is due to the delay in attaining a stable temperature reading caused by the enclosure of the probe in a thick metal casing. 	<ul style="list-style-type: none"> The temperature readings were within 5°C of a calibrated K-Type Thermocouple. This was deemed accurate. 	<ul style="list-style-type: none"> The only device tested that measures the in-hole rock surface temperature. The device gives temperature readings that are within less than 10°C of a calibrated in-hole air temperature measurement device. This was deemed to be accurate, also due to calibration. In some cases, the left and right infrared eyes gave differing temperatures, indicating the difference in the rock temperature on either side of the probe.
Response time	<ul style="list-style-type: none"> Temperature readings are displayed on the output device immediately, no delay in response time was observed. However, the device must be held in position for about 5 to 8 s for the temperature readings to stabilise to one reading. 	<ul style="list-style-type: none"> There is a delay of more than 1 minute approximately, between the time of immersion of the probe in the hole and the display of a stable temperature readings. The probe is enclosed in a thick metal. 	<ul style="list-style-type: none"> There is a delay of approximately less than one minute between the time of immersing the cable into the hole and the readings of temperature values from the mobile phone due to potential network issues. 	<ul style="list-style-type: none"> Temperature readings are displayed on the output device immediately, no delay in response time was observed.
Temperature Range	<ul style="list-style-type: none"> The device was used successfully to detect temperatures of up to 198°C at the test site and temperatures of up to 500°C on a production bench at Mine A. However, the wire gets damaged at these high temperatures, which may lead to incorrect readings. 	<ul style="list-style-type: none"> The device was used in holes with in-hole air temperatures of up to its maximum specification of 127°C, however, due to its slow response time to heat, the device was only used for less than 10 holes. 	<ul style="list-style-type: none"> Up to 127°C. The device was used successfully to detect temperatures within the specified range (up to 127°C) and at the test site. The device was not used in holes of greater temperatures due to heating up of the wire and sensors. 	<ul style="list-style-type: none"> Ambient temperature range: 0°C to 75°C. Object temperature range: -20°C to 350°C. The device was used successfully to detect temperature of up to 150°C; this was a measure taken to avoid damage to the device since replacing it is expensive.
Length of temperature measuring wire, cable, or string	<ul style="list-style-type: none"> The thermocouples tested were of different lengths, with the longest at a length of 30 m; thus accommodating holes of depths of less than 30 m. Wires of different lengths can be ordered from the supplier. Wire cut offs (and cable re-joining) may result in shorter wires over time, as witnessed in the tests. 	<ul style="list-style-type: none"> The length of the device was sufficient for holes of up to 25 m. The thermocouple wire is susceptible to damage over time in hot holes, which may lead to cut-offs and thus resulting in a shorter wire. 	<ul style="list-style-type: none"> The devices tested were of a single-length cable (25 m) and the corresponding sensors placed at 1 m intervals. The length of the cable is a limitation in the event that temperature measurements for hole with depths greater than 25 m need to be taken. 	<ul style="list-style-type: none"> The cable length of the device tested was 30 m. The length of the cable is not a limitation since most holes at the mine are less than 30 m and cables of any length, depending on the deepest hole at the production site, can be ordered from the manufacturer.

Criteria	K-Type Thermocouple (Sinometer)	K-Type Thermocouple (Fluke)	Temperature Log (QMR)	Blast Hole Temperature Logger (Insight Technical Support)
Durability of the wire, string, cable or the device or probe	<ul style="list-style-type: none"> The wires are covered in thin plastic insulation. The wire heats up in hot holes and becomes susceptible to breaking and short circuiting due to wear and tear overtime. This may lead to incorrect/inaccurate temperature readings. 	<ul style="list-style-type: none"> The wires are covered in thin plastic insulation. The wire heats up in hot holes and becomes susceptible to breaking and short circuiting due to wear and tear overtime. This may lead to incorrect/inaccurate temperature readings. The probe, however, is enclosed in a metal casing which protects it from high temperatures; this is also the weakness of the device as it records inaccurate temperatures. 	<ul style="list-style-type: none"> The cable and sensors are covered in thick plastic insulation. The cable heats up in hot holes but can better withstand wear and tear because of the insulation. Damage to the insulation may lead to damage of the cables and sensors which may lead to malfunctions and incorrect/inaccurate temperature readings. 	<ul style="list-style-type: none"> The wires are covered in a thick layer of insulating sheath. Although the cable heats up in hot holes, it is less susceptible to wear and tear. The connection between the probe and the cable is susceptible to bending and twisting which may lead to breaking of the inner wires. The probe is prone to scratches, and it is exposed to water, dust and mud. However, the inner surface of the lens is protected by a disposable outer layer lens that is easy to replace if it gets scratched or burnt by heat.
Instrument set up time	<ul style="list-style-type: none"> The thermocouple wire is connected to the thermometer reader within a duration of 30 s. Setup delays may be due to the entanglement of the wire and malfunctioning of the wire or the thermometer. 	<ul style="list-style-type: none"> The thermocouple wire is connected to the thermometer reader within a duration of 30 s Setup delays may be due to the entanglement of the wire and the malfunctioning of the wire or the thermometer. 	<ul style="list-style-type: none"> Connecting the sensing cable to the power source and the output device (mobile phone or laptop) takes approximately 1 minute or less. Setup delays may be due to poor Bluetooth connectivity, or power source malfunctions. 	<ul style="list-style-type: none"> Connecting the cable to the output display device takes approximately less than 1 minute. Setup delays may be due to the unease in aligning the connector to the socket (which may be dirty), inputting set up data and solving errors arising from setting up. The thickness and smooth texture of the cable reduces the possibility of delays due entanglement. Set up time is also affected by the experience of the user.
Position of temperature measurement in the hole (single or multiple point)	<ul style="list-style-type: none"> Single-point temperature reading per instance. To construct a temperature profile of the hole, temperatures at specific depths would have to be taken manually. 	<ul style="list-style-type: none"> Single-point temperature reading per instance. To construct a temperature profile of the hole, temperatures at specific depths would have to be taken manually. 	<ul style="list-style-type: none"> Multiple points of measurements per instance, producing a temperature profile of the hole along its depth. 	<ul style="list-style-type: none"> The probe of the device has two infrared eyes that each have a 180° range, which enables temperature detection throughout the circumference of the hole. The probe takes 5 readings per second and records the hottest reading on the output device from each eye every second. Temperature readings are logged as the cable is moved up and down the hole, in this way, a temperature profile of the hole can be constructed.

Criteria	K-Type Thermocouple (Sinometer)	K-Type Thermocouple (Fluke)	Temperature Log (QMR)	Blast Hole Temperature Logger (Insight Technical Support)
Visibility of temperature readings and warning lights	<ul style="list-style-type: none"> Temperature readings on the LCD screen of the multimeter are visible but not clearly under direct sunlight. In the dark, a light source is required. 	<ul style="list-style-type: none"> Temperature readings on the LCD screen of the multimeter are visible but not clearly under direct sunlight. In the dark, a light source is required. 	<ul style="list-style-type: none"> The output display unit is a mobile phone or a laptop thus, visibility of the temperature readings is good since background lighting is adjustable. 	<ul style="list-style-type: none"> Temperature readings on the LCD screen are visible but not clearly under direct sunlight. In the dark, a light source is required. The device has an option to toggle the lighting between low and bright background light settings.
Audibility	<ul style="list-style-type: none"> Not applicable 	<ul style="list-style-type: none"> Not applicable. 	Not applicable.	<ul style="list-style-type: none"> The device has the functionality to produce audible sounds on start-up, when temperature logging begins and importantly and an alarm sound when a set specific temperature is reached.

Table 16. An evaluation of temperature monitoring instruments

Criteria	Hot Hole Management System (PositionXT)	Hot hole Monitor/Blast Eye (AEL)	Multipoint Blast Eye 1 (Designs Unique)	Multipoint Blast Eye 2 (Designs Unique)	Safeblast (Ningi Services)
Accuracy	<ul style="list-style-type: none"> The alert system (alarm sound and LED lights) corresponds to the temperatures at which it is set to function. This was proven by using a K-Type thermocouple to measure the temperature in the same holes and the display node of the same device. The accuracy of the alert system may be affected by damage to the sensors (chip board) on the temperature wire, which are not enclosed. 	<ul style="list-style-type: none"> The alarm sound corresponds to the temperatures at which it is set to function. This was proven by using a K-Type thermocouple to measure the temperature in the same holes. The device functionality is flawed in that, once a specific high temperature is reached, even when cooled down, the alarm system does not go off. 	<ul style="list-style-type: none"> The alert system (alarm sound and LED lights) corresponds to the temperatures at which it is set to function. This was proven by using a K-Type thermocouple to measure the temperature in the same holes. 	<ul style="list-style-type: none"> The alert system (alarm sound and LED lights) corresponds to the temperatures at which it is set to function. This was proven by using a K-Type thermocouple to measure the temperature in the same holes. 	<ul style="list-style-type: none"> Some technical issues were experienced with the devices that were tested; in some cases, the alert system did not function in correspondence to the set temperatures. The alert system did not go off in holes that contain water; this was also experienced when the devices were immersed in boiling water used for calibration.
Response time	<ul style="list-style-type: none"> There was no delay between the time of inserting the wire in the holes and the triggering of the alert system. 	<ul style="list-style-type: none"> There was no delay between the time of inserting the wire in the holes and the triggering of the alert system. 	<ul style="list-style-type: none"> There was no delay between the time of inserting the wire in the holes and the triggering of the alert system. 	<ul style="list-style-type: none"> The sensors are enclosed in thick insulation which results in a delay of up to 1.5 minutes between the start of alert system (alarm sound and LED lights) and inserting 	<ul style="list-style-type: none"> For the devices that were not faulty, there was no delay between the time of inserting the wire in the holes and the triggering of the alert system.

Criteria	Hot Hole Management System (PositionXT)	Hot hole Monitor/Blast Eye (AEL)	Multipoint Blast Eye 1 (Designs Unique)	Multipoint Blast Eye 2 (Designs Unique)	Safeblast (Ningi Services)
				the device in a hot medium.	
Temperature Range	<ul style="list-style-type: none"> 0°C to 128°C. The device was used successfully in holes of temperatures between 28°C and 128°C at the test sites and mining blocks. 	<ul style="list-style-type: none"> Not specified. The device was successfully used in holes with temperatures greater than 60°C and greater than 80°C (up to 100°C), the temperature at which the alarm system of the device is set to trigger. 	<ul style="list-style-type: none"> Up to 128°C The device was used successfully in holes of temperatures of up to 128°C at the test sites and mining blocks. 	<ul style="list-style-type: none"> Up to 128°C The device was used successfully in holes of temperatures of up to 128°C at the test sites and mining blocks. 	<ul style="list-style-type: none"> Temperatures above 100°C. The device was successfully tested in holes of temperatures of up to 128°C at the test sites and mining blocks.
Length of temperature measuring wire, cable, or string	<ul style="list-style-type: none"> The temperature wire length of the device tested was 25 m and the corresponding sensors placed at 1 m intervals. Using the device, in-hole hot spots, located between the sensors may be missed since the sensors are spaced 1 m apart. The technical aspects on the sensing area around a sensor, which would indicate whether a 1 m optimal spacing is optimal, were however not conducted. 	<ul style="list-style-type: none"> The wire length of the devices tested was 30 m. There were no issues identified regarding the wire length. 	<ul style="list-style-type: none"> The temperature wire length of the device tested was 30 m and the corresponding sensors placed at 5 m intervals. In-hole hot spots may be missed since the sensors are 5 m apart. The technical aspects on the sensing area around a sensor, which would indicate whether a 5 m optimal spacing is optimal, were however not conducted. 	<ul style="list-style-type: none"> The temperature wire length of the device tested was 17m and the corresponding sensors placed at 5 m intervals. Other wires of variable length to suite different hole depths are available. The sensors are 5 m apart; technically by having sensors 5 m apart there is only 2,5 m between sensors and they are used to measure heating of explosives so it doesn't matter if it is not exactly at a hot spot. The technical aspects on the sensing area around a sensor, which would indicate whether a 5 m optimal spacing is optimal, were however not conducted. 	<ul style="list-style-type: none"> Devices of 15 m and 30 m lengths and sensors placed at 5m intervals were tested. In-hole hot spots may be missed since the sensors are 5 m apart. The technical aspects on the sensing area around a sensor, which would indicate whether a 5 m optimal spacing is optimal, were however not conducted.
Durability of the wire, string, cable or the device or probe	<ul style="list-style-type: none"> The wires are covered in thin plastic insulation. The sensors (chips) are exposed. The wires heat up in hot holes but, since this device is used for monitoring charged holes until blasting and is immersed in emulsion of low 	<ul style="list-style-type: none"> The wires are covered in thin plastic insulation. The wire heats up in hot holes but, since this device is used for monitoring charged holes until blasting and is immersed in emulsion of low temperatures (<40°C), the 	<ul style="list-style-type: none"> The cable and sensors are covered in thick plastic insulation. The cable heats up in the hole but the interior wires and sensors are less susceptible to wear and tear due to the insulation. 	<ul style="list-style-type: none"> The cable is covered in thick plastic insulation while the wires are covered in thick insulation. The wires heat up in the hole but since the device is designed for 	<ul style="list-style-type: none"> The cable and sensors are covered in thick plastic insulation. The cable heats up in the hole but the interior wires and sensors are less susceptible to wear

Criteria	Hot Hole Management System (PositioNXT)	Hot hole Monitor/Blast Eye (AEL)	Multipoint Blast Eye 1 (Designs Unique)	Multipoint Blast Eye 2 (Designs Unique)	Safeblast (Ningi Services)
	<p>temperatures (<40°C), the wires are protected from the direct harsh hole environment for the monitoring duration.</p> <ul style="list-style-type: none"> It is unclear whether the devices will function in holes that contain emulsion as these tests were not conducted, however, the device functions in holes that contain water. 	<p>wires are protected from the direct harsh hole environment for the duration of monitoring.</p> <ul style="list-style-type: none"> The device functioned in holes that contain emulsion. 	<p>The wire is designed for single use therefore, wear and tear may not be an issue.</p> <ul style="list-style-type: none"> The device functioned in holes that contain emulsion. 	<p>single-use and immersion in emulsion (<40°C) therefore, wear and tear may not be an issue.</p> <ul style="list-style-type: none"> The device functioned in holes that contain water. 	<p>and tear due to the thick insulation. The wire is designed for single use therefore, wear and tear are ruled out.</p> <ul style="list-style-type: none"> The majority of the 30 m cables did not function in boiling water and in holes that contain water. There was a concern on whether the devices would function in holes that contain emulsion as these tests were not conducted. However, according to the technical personnel at the mine (as of April 2022), this was a manufacturing problem that has since been resolved
Instrument set up time	<ul style="list-style-type: none"> Connecting the temperature wire to either the alarm node or the display node takes approximately less than 30 s. Set up delays may be due to entanglement of the temperature wire, mounting the alarm node to firm ground and in a position where the LED is visible from the block and errors encountered when after connecting the display monitor. 	<ul style="list-style-type: none"> The device comes as one item; thus, the setup is not time consuming, approximately less than 20 s. 	<ul style="list-style-type: none"> Connecting the cable to the output display device takes less than 30 s. Setup delays may be due to the time required to solve errors on the output display resulting from the malfunctioning of the wire sensors. 	<ul style="list-style-type: none"> Connecting the cable to the output display device takes less than 30 s. Setup delays may be due to the time required to solve errors on the output display resulting from the malfunctioning of the wire sensors. 	<ul style="list-style-type: none"> Connecting the cable to the output display device takes less than 30 s. Setup delays may be due to the time required to solve errors on the output display resulting from the malfunctioning of the wire sensors.
Position of temperature measurement in the hole (single or multiple point)	<ul style="list-style-type: none"> Multiple points of temperature measurements per instance, producing a temperature profile of the hole along its depth. 	<ul style="list-style-type: none"> Single-point temperature detection. 	<ul style="list-style-type: none"> Multiple points of temperature detection per instance, producing a temperature profile of the hole along its depth. 	<ul style="list-style-type: none"> Multiple points of temperature measurements per instance, producing a temperature profile of the hole along its depth. 	<ul style="list-style-type: none"> Multiple points of temperature measurements per instance, producing a temperature profile of the hole along its depth.

Criteria	Hot Hole Management System (PositionXT)	Hot hole Monitor/Blast Eye (AEL)	Multipoint Blast Eye 1 (Designs Unique)	Multipoint Blast Eye 2 (Designs Unique)	Safeblast (Ningi Services)
Visibility of temperature readings and warning lights	<ul style="list-style-type: none"> The display node uses ePaper; the temperature readings are visible under sunlight but in the dark, a light source is required. The LED lights are not properly aligned to the hole on the alarm node; the LEDs (if the device is placed correctly) are visible within a radius of about 1 m under sunlight. The warnings may be confusing in that there are many temperature intervals and corresponding LED colours. The output device is installed on the hole collar; its height is not sufficient to enable workers on the block to visualise the warning lights from a distance. 	<ul style="list-style-type: none"> The device does not have a display unit with warning lights. No temperature readings can be detected. 	<ul style="list-style-type: none"> The warning LEDs/lights are not clearly visible under direct sunlight. The user would have to be holding the device to assess any change in temperature and the relevant warning. No temperature readings can be displayed but, the device is set to signal warnings at specific temperature intervals. 	<ul style="list-style-type: none"> The warning LEDs/lights are not clearly visible under direct sunlight. The user would have to be holding the device to assess any change in temperature and the relevant warning. The output device is installed on the hole collar; its height is not sufficient to enable workers on the block to visualise the warning lights from a distance. Thus, a worker would be required to move to within 2 m of the device to identify the warning, especially under direct sunlight. No temperature readings can be displayed but, the device is set to signal warnings at specific temperature intervals. Temperatures can be downloaded on a computer away from the block. 	<ul style="list-style-type: none"> The warning LEDs/lights are not clearly visible under direct sunlight. The user would have to be holding the device to assess any change in temperature and the relevant warning. The output device is installed on the hole collar; its height is not sufficient to enable workers on the block to visualise the warning lights from a distance. No temperature readings can be displayed but, the device is set to signal warnings at specific temperature intervals.
Audibility	<ul style="list-style-type: none"> The alarm was found to be audible within a radius of about 15 m. NB – it is assumed that a worker who has passed the hearing test should be able to hear the alarm within this radius. Audibility is reduced by the noise from other equipment on or near the bench such as drill rigs and explosives trucks. 	<ul style="list-style-type: none"> The alarm was found to be audible within a radius of about 15 m. NB – it is assumed that a worker who has passed the hearing test should be able to hear the alarm within this radius. Audibility is reduced by the noise from other equipment on or near the bench such as drill rigs and explosives trucks. 	<ul style="list-style-type: none"> The alarm was found to be audible within a radius of about 15 m. NB – it is assumed that a worker who has passed the hearing test should be able to hear the alarm within this radius. Audibility is reduced by the noise from other equipment on or near the 	<ul style="list-style-type: none"> The alarm was found to be audible within a radius of about 15 m. NB – it is assumed that a worker who has passed the hearing test should be able to hear the alarm within this radius. Audibility is reduced by the noise from other 	<ul style="list-style-type: none"> The alarm was found to be audible within a radius of about 15 m. NB – it is assumed that a worker who has passed the hearing test should be able to hear the alarm within this radius. Audibility is reduced by the noise from

Criteria	Hot Hole Management System (PositioNXT)	Hot hole Monitor/Blast Eye (AEL)	Multipoint Blast Eye 1 (Designs Unique)	Multipoint Blast Eye 2 (Designs Unique)	Safeblast (Ningi Services)
	Other environmental conditions such as wind direction may also distort the alarm sound.	Other environmental conditions such as wind direction may also distort the alarm sound.	bench such as drill rigs and explosives trucks. Other environmental conditions such as wind direction may also distort the alarm sound.	equipment on or near the bench such as drill rigs and explosives trucks. Other environmental conditions such as wind direction may also distort the alarm sound.	other equipment on or near the bench such as drill rigs and explosives trucks. Other environmental conditions such as wind direction may also distort the alarm sound.

5.2 The evolution of hot hole temperature from drilling to ignition

The temperature of holes at the two test sites and those at various production blocks were monitored over time to identify trends that may be useful in the planning and execution of blasts in hot mining environments. It is noteworthy that the holes at the two test sites were older (in comparison to the freshly drilled ones at the actual mining blocks), hence, they were not monitored “*from drilling*” to ignition as depicted in the heading. The importance of understanding the day-to-day change in temperature of these holes, however, cannot be overstated. The K-type thermocouple and digital thermometer were used for the majority of the tests to measure the in-hole air temperature. This device has its strengths and weaknesses as described in section 5.2 of the report. The measurements were supplemented, to a lesser extent, by using an infrared device which measures the in-hole rock temperature (also assessed in detail in section 5.2). To safeguard the infrared device, which is considerably more expensive than the K-Type thermocouple, the device was not used in holes with temperatures exceeding 150°C (based on the K-Type thermocouple measurements). The K-Type thermocouple was used to measure the in-hole air temperature at the bottom of the hole and the maximum in-hole air temperature of the hole. Similarly, the infrared device was used to measure the in-hole rock temperature at the bottom of the hole and the maximum in-hole rock temperature of the hole.

At the actual mining blocks, temperature measurements were dependent on the drill and blast schedule. In some blocks, holes were drilled and left uncharged for more days than in other blocks. Furthermore, the number of holes monitored varied amongst the different blocks. This was dependent on the availability of a safe environment to carry out measurements since in some cases, there were drill rigs in the vicinity of the block. In these instances, sections of the block had to be re-drilled and during the drill rig manoeuvre, some holes would be closed or blocked off resulting in no further temperature measurements in those holes. In other instances, tests on gas bags and foam plugs were conducted simultaneously in the same holes, leading to disruptions in temperature measurements in those holes.

5.2.1 Test Site 1 results

At Test Site 1, the in-hole air temperature of the 52 holes was measured on 10 random days within the four weeks spent at the test site using the K-Type thermocouple. The results are illustrated in Figure 46. In the graph, each slice (into the page) represents a hole, and the slice is made up of columns which represent a day on which a temperature measurement was taken. The height of the column represents the maximum in-hole air temperature of the particular hole on that day. The general trend, as shown in Figure 46, is that the in-hole air temperature changed minimally. In fact, the average of the net change in the maximum in-hole air temperature (Equation 1), calculated as the sum of the differences between two maximum in-hole air temperatures measured on consecutive days, was calculated to be - 4.2°C. This value is, however, inflated by a significant temperature drop in Hole 29 and Hole 39 in which gas bags were inserted close to the bottom of the holes at the start of the tests. Excluding these holes leads to an average net in-hole temperature change of approximately - 2°C. This means that, in general, the maximum in-hole air temperature of the holes at Test Site 1 decreased by approximately 2°C per hole.

$$\Delta \text{Temperature} = \Sigma(\text{Temperature Day 2} - \text{Temperature Day 1}) \quad \text{Equation 1}$$

Where;

Δ Temperature – the net change in the maximum in-hole temperature of the hole (°C)

Temperature Day 2 – the maximum in-hole air temperature on the succeeding day (°C)

Temperature Day 1 – the maximum in-hole air temperature on the preceding day (°C)

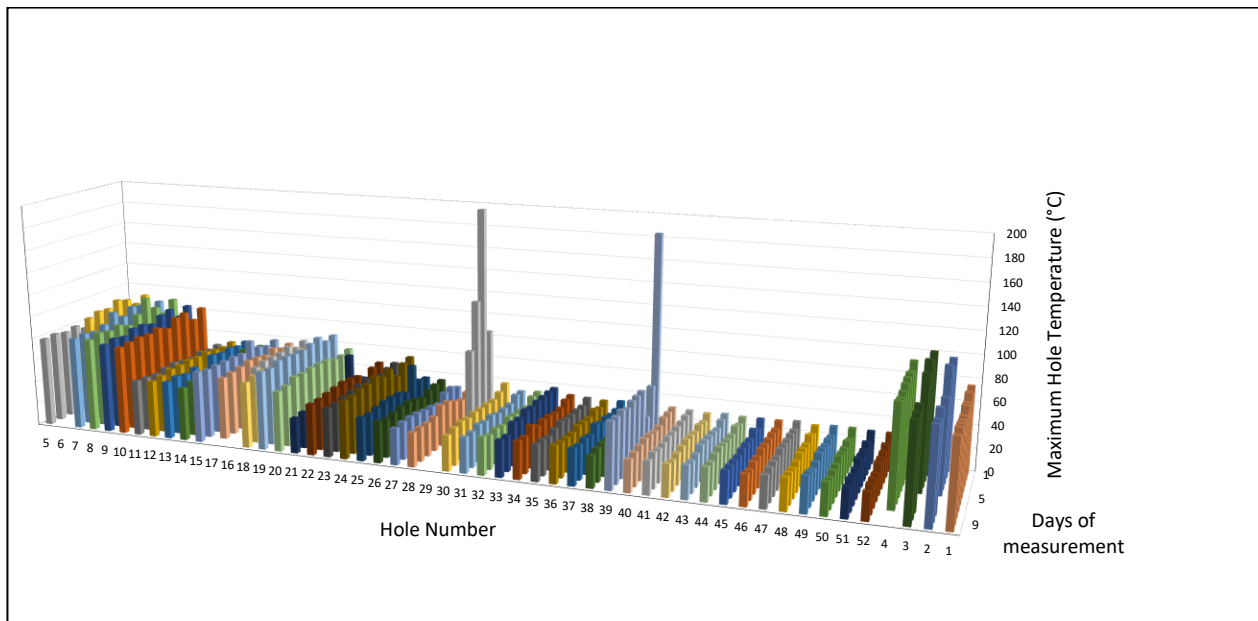
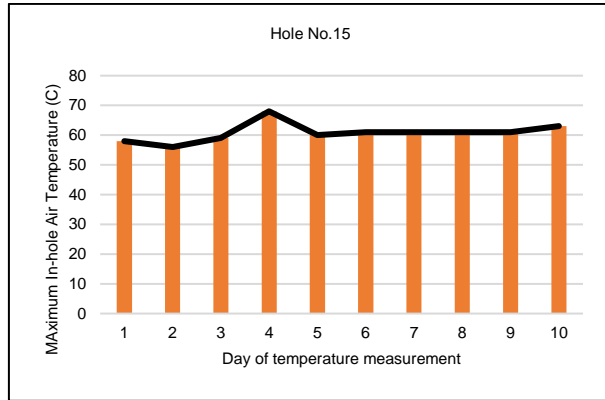
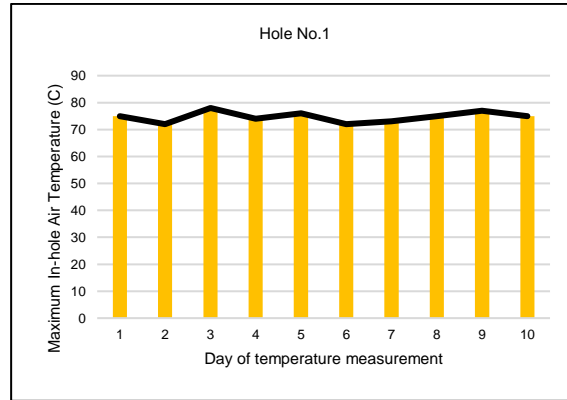


Figure 46. A trend of maximum in-hole air temperatures overtime at Test Site 1

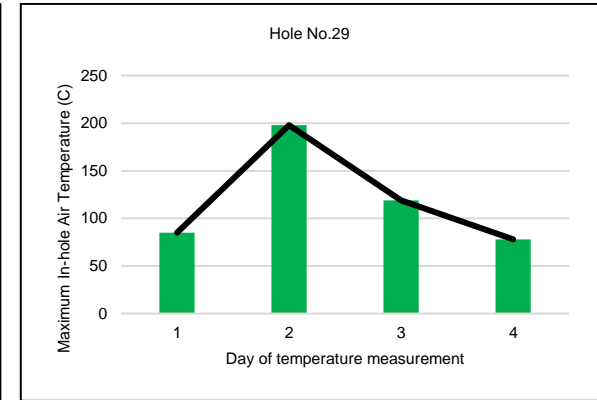
The significant change in the in-hole temperature of Hole 29 and Hole 39 is attributed to the blockage of the hole with gas bags in positions other than those where the maximum in-hole air temperature was initially measured. Thus, subsequent measurements were taken above the gas bag position, at positions higher up in the hole. Temperature readings for Hole 29 (Figure 47c) were eventually discontinued. Figure 47 shows the in-hole air temperature change for Holes 1, 15 and 29. In Hole 15 (Figure 47a), the net change in the in-hole air temperature was calculated to be 5°C. This is one of the minority holes in which the in-hole air temperature increased over the 10 days of measurement, although the increase was small. In some holes, such as Hole 1 (Figure 47b), the temperature remained fairly constant, as characterised by a net in-hole air temperature change of 0°C.



(a)



(b)



(c)

Figure 47. The in-hole air temperature change for three holes

5.2.2 Test Site 2 results

Monitoring the temperature change of holes over time at Test Site 2 was hindered by the availability of a rugged enough, yet accurate temperature monitoring device, as most of the holes had temperatures in excess of 200°C. An improvised temperature probe made of a 25 m of aluminium wire, which was connected to a K-Type digital thermocouple was used for these holes. Table 17 shows the in-hole ambient temperatures detected by this device for some of the hottest *bhoboza* holes. The temperatures stabilised after approximately 5 minutes of inserting the aluminium probe into the hole. It should be noted that since the whole aluminium wire acts as the probe, the relationship between temperature increase and depth could not be established. It is however, assumed that since the holes holed through to underground workings, the source of the heat is at the bottom of the hole. Tests on foam expander plugs were later conducted in these holes; thereby distorting the accuracy of the temperature of the holes.

Table 17. Temperature of *bhoboza* holes at Test Site 2 using an aluminium probe

Hole Number	Day 1		Day 2	
	Initial Temperature (°C)	Maximum Temperature after 5 minutes (°C)	Initial Temperature (°C)	Maximum Temperature after 5 minutes (°C)
1	331	340	302	333
2	318	324	281	312
3	258	258	198	273
4	92	161	105	174
5	256	260	157	249
6	106	152	89	154
7	264	341	243	310
8	338	393	303	387
9	108	200	123	226

5.2.3 Mining Block 1 results

The monitoring of holes from drilling until prior to charging continued at actual mining blocks at Mine A. An example of a mining block on which monitoring was conducted is shown in Figure 48. The same methodology was followed, in which, the in-hole air temperature was measured using the K-Type thermocouple and meter. The in-hole air temperature at the bottom of the hole and the maximum in-hole temperature were recorded. Figure 49 shows a trend of maximum in-hole air temperatures recorded in 32 holes at Mining Block 1. Similar to the holes at the test site, the general trend for the holes at this mining block shows a minimal change in the in-hole air temperature. The average net change in the in-hole air temperature was found to be -1°C. The in-hole air temperature of the holes thus, decreased by an average of 1°C per hole.



Figure 48. A mining block at which monitoring of holes was conducted

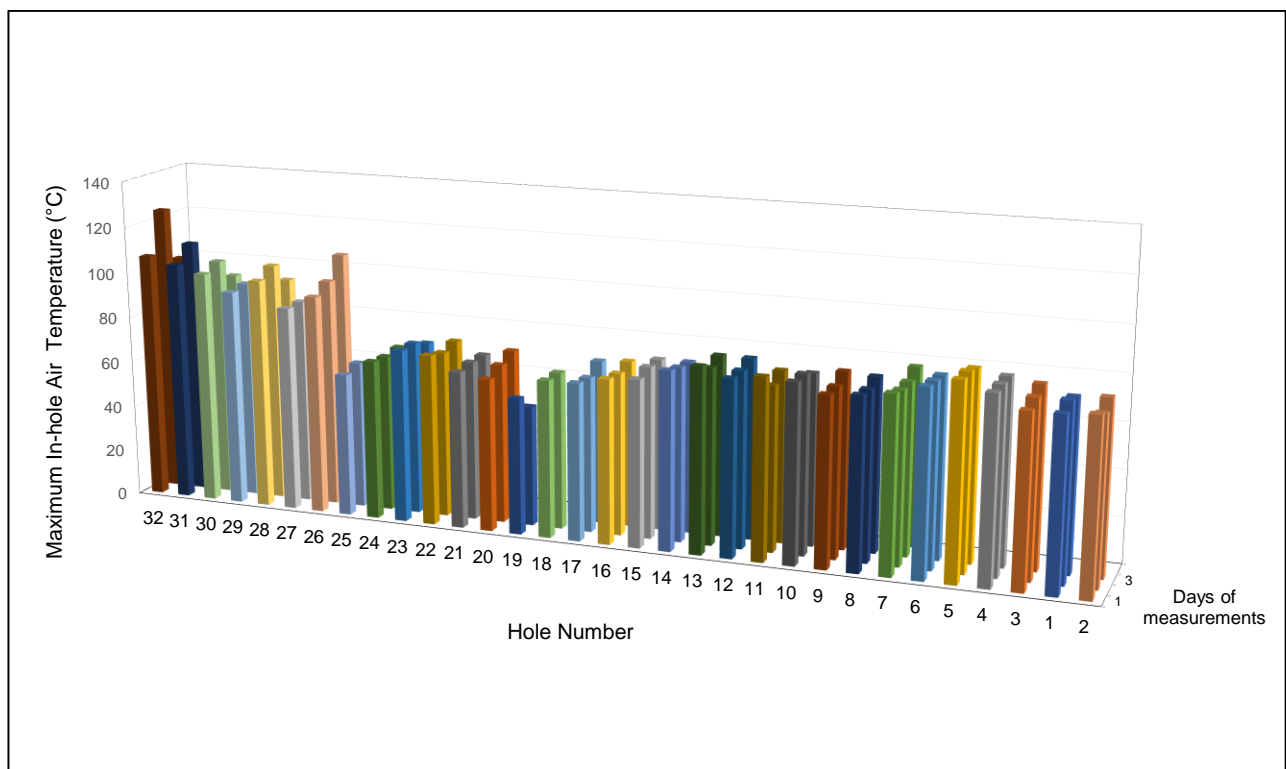
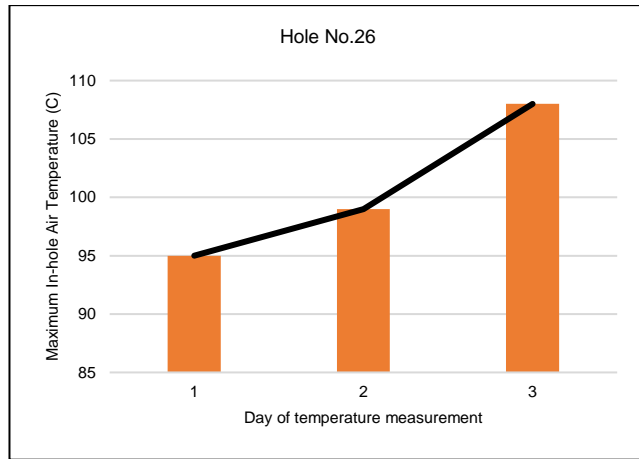
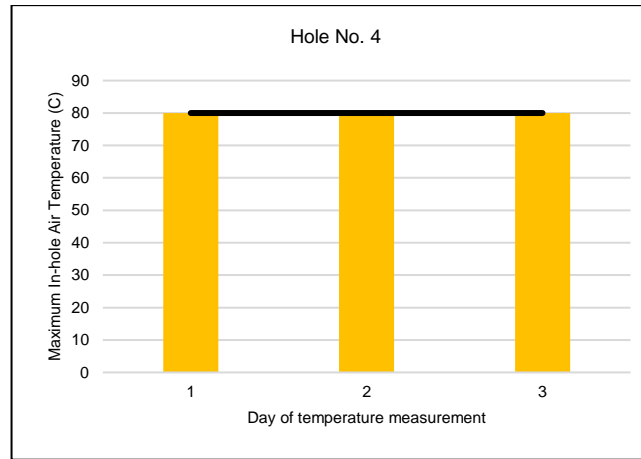


Figure 49. A trend of maximum in-hole air temperatures overtime at Mining Block 1

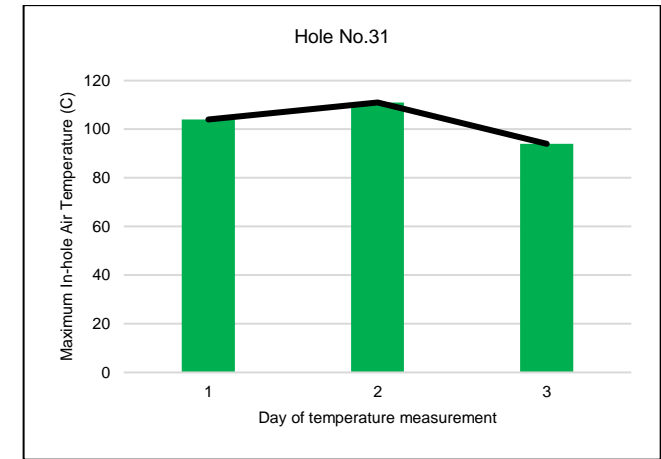
The in-hole air temperature of about 38% of the holes at Mining Block 1 increased, whereas in about 44% of the holes the in-hole air temperature decreased. The remainder of the holes had a net in-hole temperature change of 0°C. Examples of holes in which the temperature increased, decreased, or remained constant are depicted in Figure 50.



(a)



(b)



(c)

Figure 50. The in-hole air temperature change in three holes at Mining Block 1

Figure 50a shows an increase in the in-hole air temperature of hole number 26. The temperature increased by 13°C during the three days of measurement. In hole number 4 (Figure 50b), the in-hole air temperature remained constant at 80°C over the monitoring period. Although the in-hole air temperature in hole number 31 (Figure 50c) increased on the second day of measurement, the overall net change in the temperature was -10°C.

5.2.4 Mining Block 2 results

The results from Mining Block 2 were found to be almost in total contrast to those from the two test sites and the Mining Block 1. As shown on the graph in Figure 51, the height of the columns is not as uniform as the aforementioned results of the other sites. The contrast is also visible from the calculation of the average net change in the in-hole air temperature which gives a value of +5.3°C for the block. More than half of the holes at Mining Block 2, had a positive increase in the in-hole air temperature and there was only one hole whose net change in the in-hole air temperature remained 0°C, that is, the temperature remained fairly constant in the hole for the duration of the tests.

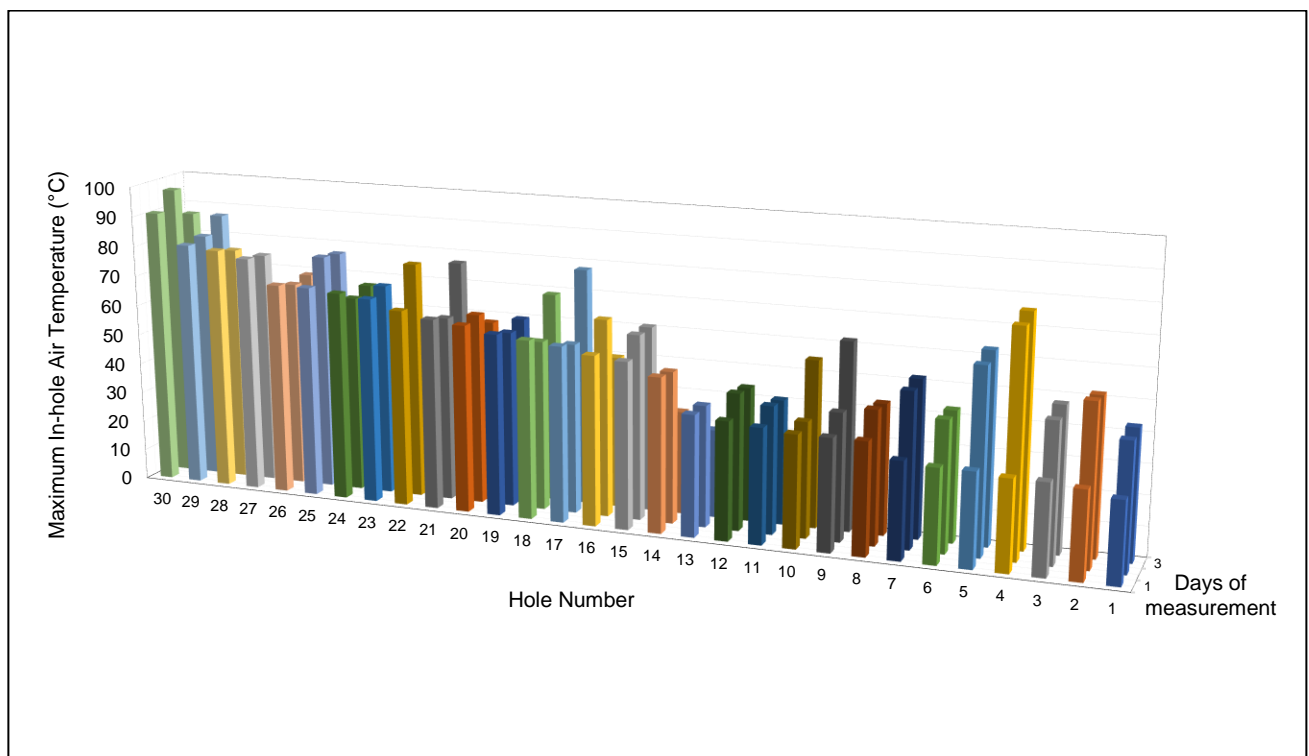
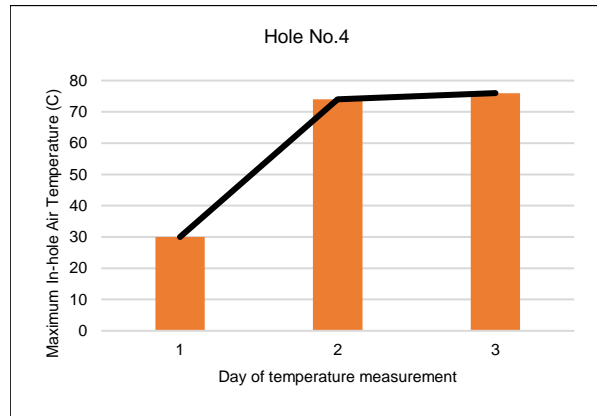
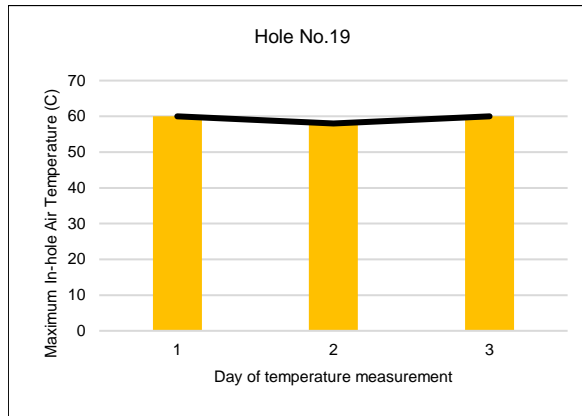


Figure 51. A trend of maximum in-hole air temperatures overtime at Mining Block 2

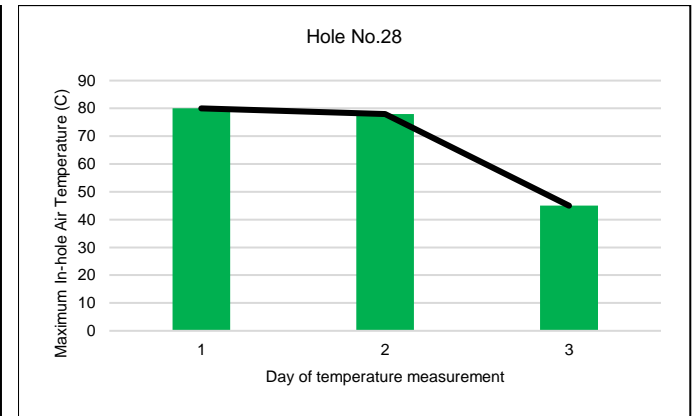
The maximum in-hole air temperatures of Hole Number 4 for the duration of measurement are depicted in Figure 52a. The in-hole air temperature of the hole increased by a net value of 46°C over the three days of measurement. This is a considerable increase in temperature compared to the previously discussed results. The one hole in the block that had a constant in-hole air temperature is shown in Figure 52b. Figure 52c shows Hole Number 28, in which the net change in the in-hole temperature amounted to -35°C. This is in direct contrast to Hole Number 4, yet both holes were on the same block.



(a)



(b)



(c)

Figure 52. The in-hole air temperature change in three holes at Mining Block 2

5.2.5 Mining Block 3 Results

At the third mining block, 95 holes were monitored over 5 days. There was a positive net change in the in-hole air temperature in 43 holes whereas a negative change in the in-hole air temperature was found in 38 of the 95 holes. The rest of the holes had a uniform in-hole air temperature throughout the duration of measurements. For block 3, the average net change in the maximum in-hole air temperature was a positive 1.5°C. This trend, over the duration of measurement, is shown in Figure 53.

There was a significant increase in the maximum in-hole air temperature in Hole Number 16 as depicted in Figure 54a. The maximum temperature rose from 24°C on day 4 to 63°C on day 5; the hole transitioned from a *normal* hole to a hot hole within 24 hours. In hole Number 9 (Figure 54b), the temperature remained constant at about 43°C for the five-day duration. A constant drop in the in-hole air temperature from a maximum of 77°C on the first day to 67°C on the fifth day was observed in Hole Number 70 (Figure 54c).

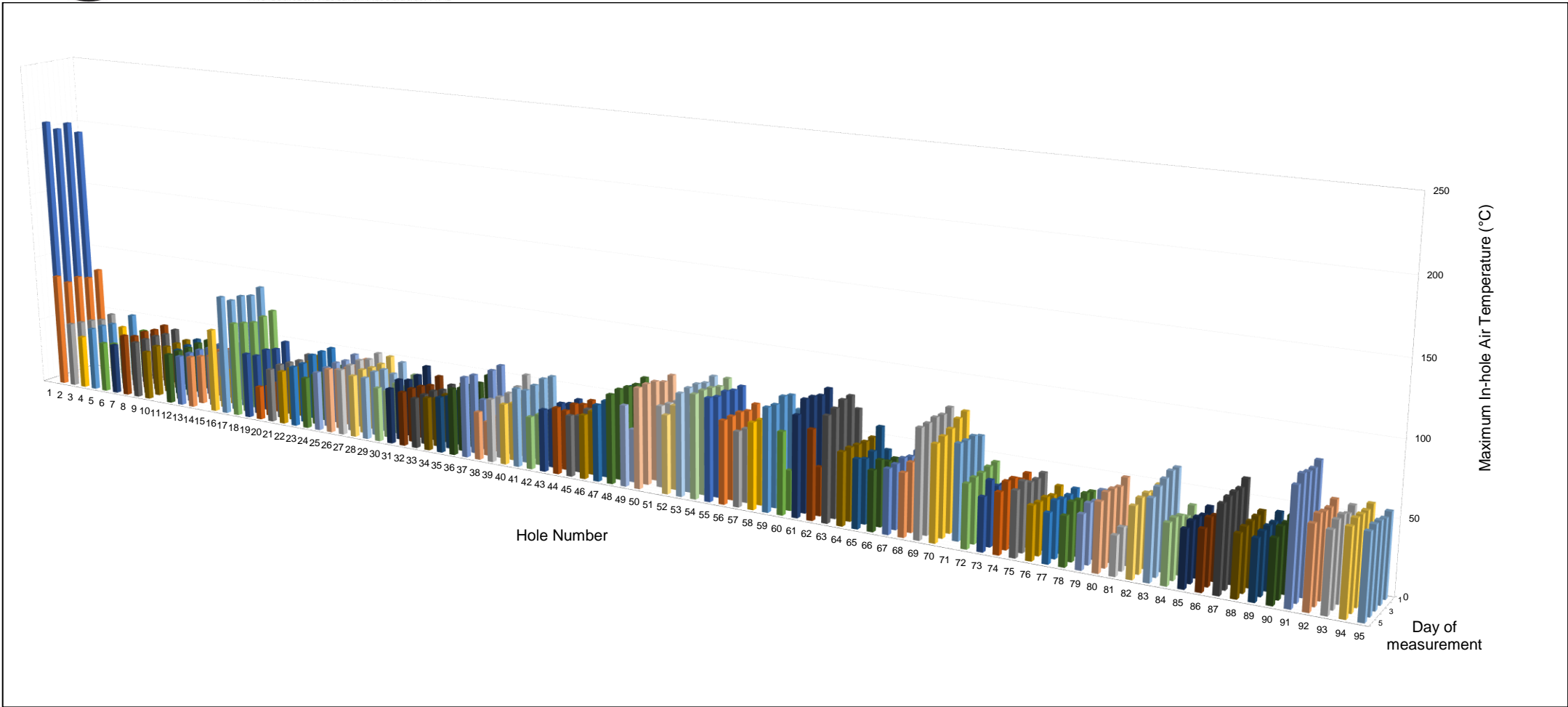
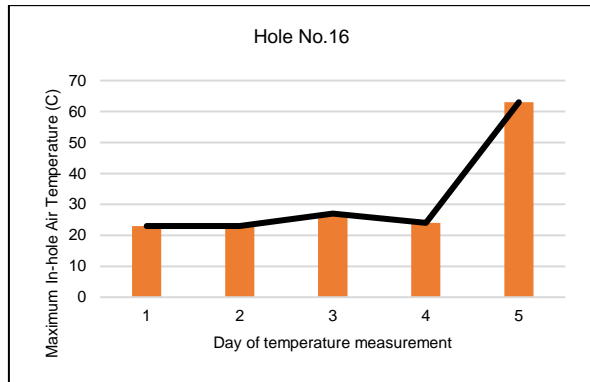
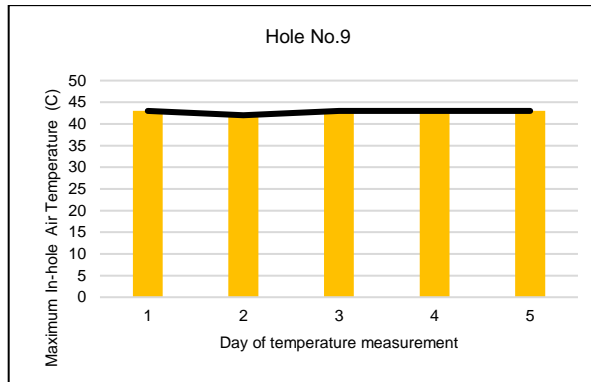


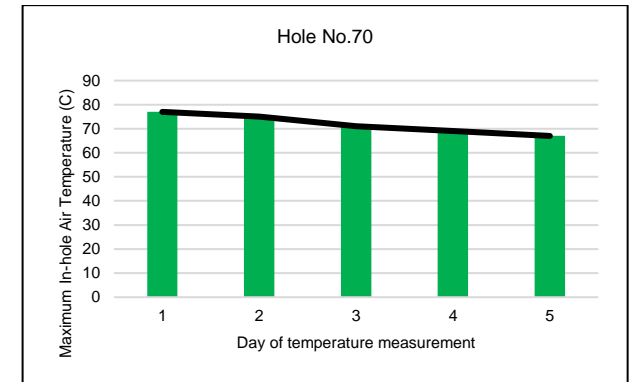
Figure 53.A trend of maximum in-hole air temperatures overtime at Mining Block 3



(a)



(b)



(c)

Figure 54. The in-hole air temperature change in three holes at Mining Block 3

5.2.6 Interpretation of the results

The tests were conducted to understand the behaviour of holes from immediately after they are drilled until prior to charging, and the tests displayed varying results. In two out of the three mining blocks (Mining Blocks 2 and 3), the majority of the holes had an increase in the maximum in-hole air temperature, in some cases, with increases of over 40°C. Thus, the average net change in temperature of these blocks was positive. Contrary to the results of Mining Blocks 2 and 3, the results of Mining Block 1 showed a decrease in the in-hole air temperature resulting in a negative net change in the temperature over the duration of the measurement. However, in this block, one hole had an increase in the in-hole air temperature of 13°C. For all the blocks, there were some holes in which the temperature remained constant, with either a decrease or increase in the in-hole air temperature of 2°C or less.

The evolution of temperature was also monitored at the two test sites, although, it should be noted that the holes were not newly drilled as those at the mining blocks. At Test Site 1, where the holes were about 6 months old at the time of investigation, the in-hole air temperature of the majority of the holes remained constant, with small decreases of 2°C or less. A small number of holes at this test site experienced an increase in the in-hole air temperature of approximately 2°C. The holes at Test Site 2 were about 3 months old when the measurements were taken. These holes were generally deeper and hotter than those at the first test site.

The results show that within a block, individual holes behave differently over time. Additionally, the temperature of the holes can increase, decrease or stay the same for the period between drilling and blasting. The increase in temperature in the holes is a major safety hazard and the main factor of consideration in the management of hot holes. As shown in the results, some holes change from normal to hot (as per the regulatory definition of hot holes) within a day. Furthermore, even though the majority of the holes on a block may display minimal temperature changes, a single hole can increase in temperature ten-fold. This is the hole that may lead to the self-detonation or premature detonation of explosives on the block.

Variations in the temperature of the holes may have been caused by the effects of weather changes on the different days of measurement. However, the impact of the weather could not be quantified. The blasting of adjacent mining blocks to those in which temperature measurements were conducted may have resulted in the increase in the in-hole air temperature of some holes. For instance, in Mining Block 3, some holes maintained a constant temperature over the first four days but on the fifth day, the temperature increased significantly (e.g., Hole Number 16). This coincided with the blasting of the block next to Mining Block 3 on the fourth day of temperature measurement.

These results are based on the assumption that the instruments used gave accurate readings for the duration of the measurements. Technical issues may have distorted the temperature measurements leading to false increases or decreases in temperature. Other factors that may have affected the temperature readings are:

- Incorrect or inconsistent positioning of the instrument within the hole – water and mud in the hole may lead to a temperature being read at a position other than the bottom of the hole

- The failure to continuously monitor the thermometer that displays readings while retrieving the thermocouple wire from the hole – this may lead to an omission of the “real” maximum temperature of the hole
- Insufficient time allowed for the instrument to stabilise and display the correct reading
- The presence of water and mud in the holes.

5.3 Evaluation of gas bags

Three gas bag products of varying dimensions and features, from three manufacturers were available for tests (Figure 55). Gas Bag 1 (*Blastbag™ Evo*) is a product from the MTi group, an Australian company. The gas bag contains an aerosol can, which when depressed releases a gas which fills the bag, causing it to expand. The gas bag is designed for use in blast holes of up to 60 °C. Gas Bag 2 (*Blast Bag™ Nero*), also manufactured by the MTi group is made of fibre webbing (cloth-like material) compared to other products that are polymer-based. The product is designed for environments with temperatures that are not greater than 120 °C and in holes of diameters ranging from 160 mm to 230 mm. Gas Bag 3 (*Kool Kap® Down Under Bag*) is a polymer-based gas bag manufactured by PR Polymers, an Australian company. The company produces two types of gas bags, one for use in hot holes with temperatures between 80°C – 100°C and the other for use in hot holes of temperatures between 100°C – 120°C.



Figure 55. Three types of gas bags tested

Limitations to the tests, that may have interfered with the accuracy of the results include the following:

- The gas bags expand before they reach the bottom of the hole
- They burn in venting holes

Further details on the gas bag tests are found in Appendix B – Gas Bag **Tests**)

5.3.1 Test results for the Gas Bag 1

The gas bags were tested in holes of varying temperatures and depths at the test site. A total of 26 gas bags were tested. Most of the bags (40%) were tested in holes with a temperature range of 50°C - 59°C as illustrated in Figure 56. The tests were also conducted in four holes with temperatures exceeding 80°C to determine how these high temperatures affect the functionality of the bag.

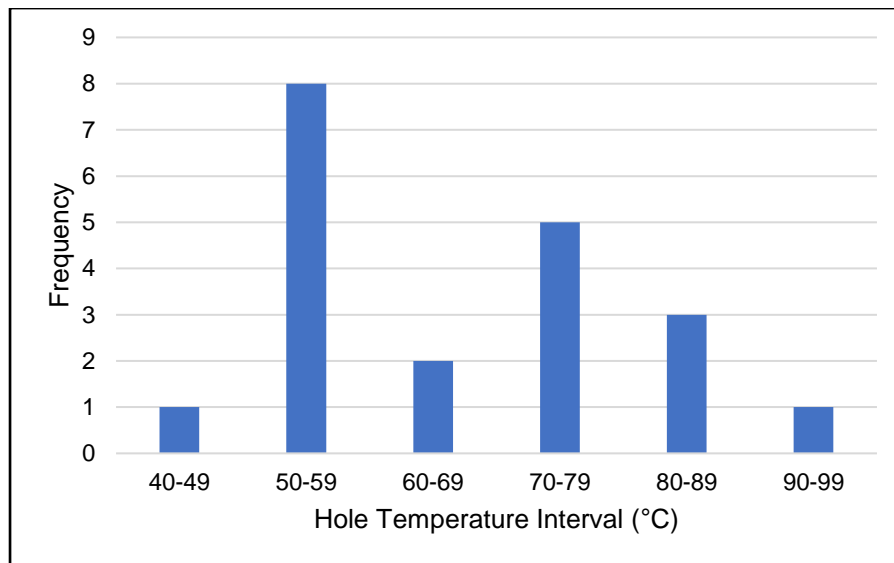


Figure 56. The number of tests for Gas Bag 1 and the corresponding hole temperatures

Temperature readings taken over time in various holes in which the tests for Gas Bag 1 took place are shown in Figure 57. In general, the temperature below the gas bag was found to be higher than the temperature on the gas bag and the temperature above the gas bag as initially anticipated. This is because in most holes, the temperature decreases upwards towards the crest of the hole due to the source of the heat being at the bottom of the hole. Therefore, the thermocouple positions above the bag coincide with hole positions that are of a lower temperature. The average difference in temperature between the thermocouple placed below the bag and the one placed on the bag was 6°C. The temperatures above the gas bag were found to be less than the temperature on the gas bag by an average of 2.3°C.

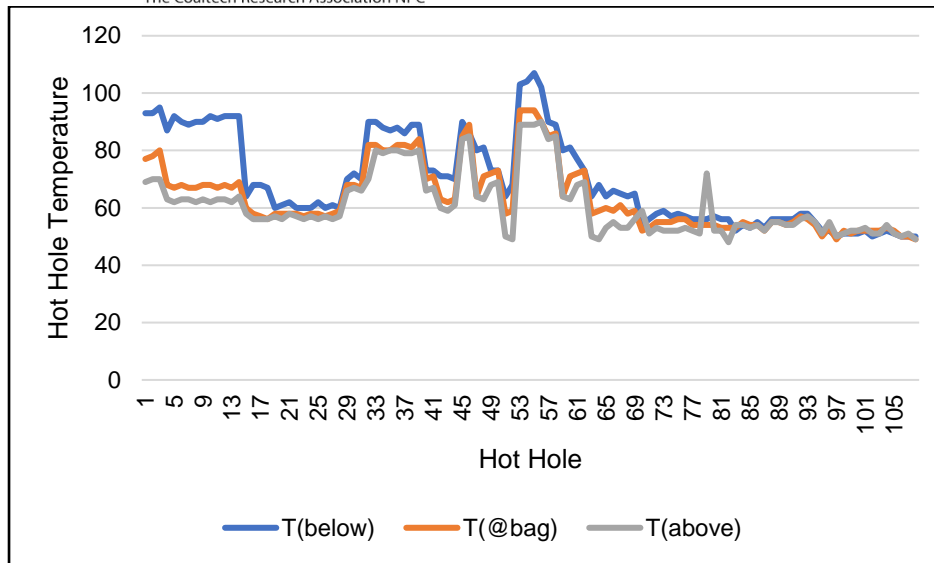


Figure 57. Hot hole temperatures for all Gas Bag 1 Tests

Based on these results, it is not clear whether the difference in temperatures from the three positions in the hole is due to some insulation provided by Gas Bag 1 or due to the temperature profile of the hole (decrease in temperature in the upward direction within the hole). The accuracy of the temperature readings could have been affected by the unequal distance between thermocouples and the condition of the thermocouple in the hole.

A further analysis of the results focused on the time it takes for Gas Bag 1 to last in the hot hole. Figure 58 shows a plot of time-to-failure against the average temperature at the gas bag. It had been anticipated that Gas Bag 1 would last longer in hot holes with temperatures of 60°C or lower as this is the maximum temperature given by the manufacturer. However, there was no clear correlation found between temperature and time-to-failure. From the 8 bags tested in hot holes between 50°C and 59°C, three bags lasted for durations of 20.8 hours, 18.5 hours and 18.3 hours. A further three bags lasted for a duration of 1 minute each in the hot hole and one bag lasted for a duration of 36 minutes before it burst or deflated. There was an anomaly identified in one of the gas bags; the bag did not fully inflate while in the hot hole.

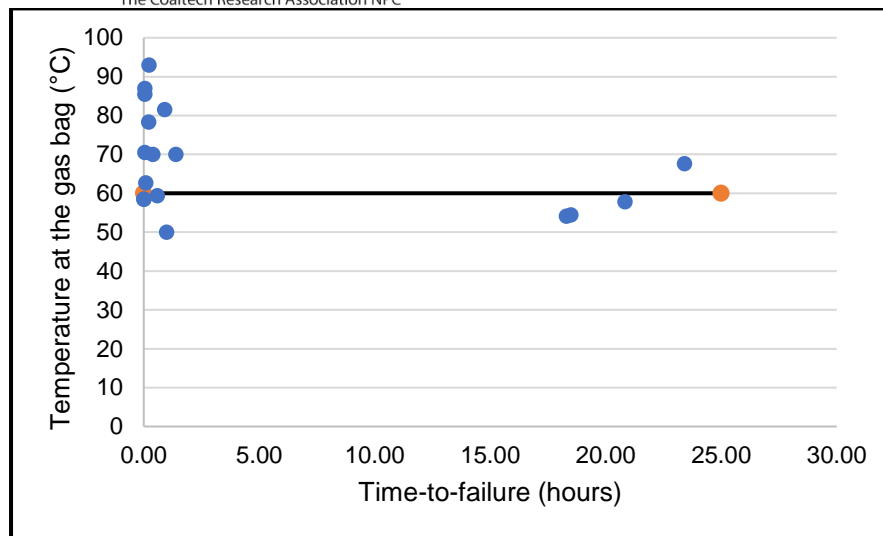


Figure 58. Time-to-failure for Gas Bag 1 against average hot hole temperature at the gas bag

Most of the gas bags tested in holes with temperatures greater than 60°C lasted for a duration of less than 1.4 hours as illustrated by the grouping of data in Figure 58. This suggests that Gas Bag 1 should not be used at these temperatures, and this is consistent with the manufacturer limit of 60°C. In contrast, one gas bag with a temperature of 68°C lasted for almost 24 hours in the hole.

The test results suggest that Gas Bag 1 does not last for a period of 24 hours or longer in a hot hole of temperatures greater than 43°C and thus are not recommended for overnight use in production hot holes. However, it is noteworthy that since these are unprecedented tests and a sample size of 20 bags was used, a bigger sample size may have resulted in a different outcome.

5.3.2 Test results for Gas Bag 2

The sample size for tests on Gas Bag 2 was limited to the bags that were available for testing. Two bags were tested in holes of 22 m and 14 m in depth respectively. When Gas Bag 2 was inserted in the hot hole; the initial temperatures below the bag, on the bag and above the bag were 195°C, 90°C and 70°C respectively. Overtime, these temperatures decreased to average temperatures of 112°C, 69°C and 59°C as shown in Table 18. The bag was monitored over a period of 5 days (120 hours) and during this time, the bag remained inflated. The time-to-failure of the bag for test 1 therefore could not be determined. The test 1 results appear to indicate that Gas Bag 2 could potentially be used in a production setting overnight, however there is a need for more tests to validate this preliminary finding.

Table 18. Test results for Gas Bag 2

Test Number	Average Temperature below bag (°C)	Average Temperature on bag (°C)	Average Temperature above bag (°C)	Time-to-failure (hours)	Total duration of monitoring (hours)
1	112	69	59	Unknown	>120
2	92	79	78	4.5	4.5

The results for Test 2 however, contradicted those of Test 1. Gas Bag 2 was inserted in a hole with average temperatures of 92°C, 79°C and 78°C for positions below the bag, on the bag and above the bag respectively. The bag lasted 4.5 hours in the hole before it deflated. The gas bag was retrieved from the hole and on inspection a puncture hole was found as depicted in Figure 59.



Figure 59. A puncture gas bag after retrieval from the test hole

The results for Gas Bag 2 are inconclusive due to the small sample size. Further tests may give better insight of the performance of these gas bags. The bag did provide some insulation as shown by the differences in temperature at the three positions in the hot hole, although this may just be coincidental to a decrease in temperature from the bottom to the crest of the hole.

5.3.3 Test results for Gas Bag 3

Two types of Gas Bag 3 were tested. The sample size was limited to the bags that were available for testing. The results are described in the following subsections.

A. Gas Bag 3 (80°C - 100°C)

The first type of Gas Bag 3 is designed for use in holes of temperatures between 100°C and 120°C. Two tests were conducted as shown in Table 19. In the first test, the average temperatures below the bag, on the bag and above the bag were 85°C, 81°C and

76°C respectively. The bag was left in the hole overnight and on inspection the following morning, the bag had deflated. Although the time-to-failure could not be determined, the bag was monitored for about 5 hours in the hole on the first day. The gas bag deflated before a 24-hour period. There no puncture holes found on the bag, but rather a small opening, presumably, from bursting.

Table 19. Test results for Gas Bag 3 with a temperature range of 100°C -120°C

Test Number	Average Temperature below gas bag (°C)	Average Temperature on gas bag (°C)	Average Temperature above gas bag (°C)	Time-to-failure (hours)	Total duration of monitoring (hours)
1	85	81	76	unknown	5
2	89	89	84	unknown	6

Similarly, for the second test, the time-to-failure could not be determined because the gas bag was left overnight in the hole. The gas bag remained inflated on the first day for 6 hours of monitoring and on the following morning, it had deflated

For both tests, the temperature differences between the positions in the hot hole were less than 6°C. For the second test, there was no difference between the temperature below the gas bag and the temperature on the gas bag. The results for the tests are inconclusive, however, it can be implied that Gas Bag 3 does not last overnight in a hot hole. A larger sample of the gas bags needs to be tested for more accurate results.

B. Gas Bag 3 (100°C - 120°C)

The second type of Gas Bag 3 is designed for use in holes of temperatures between 100°C and 120°C. Since there were no hot holes with temperatures in this range at the test site on the days of testing, hot holes with the maximum temperatures of about 94°C and 96°C were used.

Three tests were conducted as shown in Table 3. In the first test, the gas bag was monitored for 2 hours and it was left in the hole overnight. When the gas bag was inspected on the following morning, the bag had deflated. Although the time-to-failure could not be determined, the gas bag was monitored for 2 hours in the hole on the first day. In test 3, the gas bag deflated within 30 minutes, whereas the gas bag in test 3 deflated after 2 hours.

Table 20. Test results for Gas Bag 3 with a temperature range of 100°C - 120°C

Test Number	Average Temperature below gas bag (°C)	Average Temperature on gas bag (°C)	Average Temperature above gas bag (°C)	Time-to-failure (hours)	Total duration of monitoring (hours)
1	96	96	95	unknown	2
2	96	96	96	0.5	0.5

3	94	95	84	2	2
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For the first test, there was a minimal 1°C temperature difference between the average temperature on and above the gas bag. This may have been caused by the shorter distance (compared to other tests) between the thermocouple positions in the hot hole. Alternatively, it is possible that the gas bag did not provide insulation in the hot hole. This is substantiated by test 2 results in which the average temperatures on and above the gas bag were equal. However, it would be premature to make such a conclusion, given that the sample size was small, and the duration of monitoring was 2 hours or less. Although the in-hole temperatures for the three tests were less than the design temperature range given by manufacturer (100°C to 120°C), 2 out of 3 of the gas bags failed within a period of 2 hours. This may have been due to some design defects on the bags or the combined factors of pressure and heat in an actual hot hole rather than in a test environment.

5.4 Evaluation of expanding foam

5.4.1 Test results for Sibambene Foam Expander Plugs

Foam expander plugs supplied by Sibambene Mining Supplies were available for testing. A total of ten tests were conducted in hot holes with in-hole average temperatures of between 73°C and 209°C, at Test Site 1 and on mining blocks. According to the specifications document, the product should not be exposed to temperatures above 200°C, however this temperature was exceeded in some tests to determine its functionality at temperature extremities. This is useful in cases where a foam plug is used and the temperature in the hole increases beyond 200°C unexpectedly. Figure 60 shows the preparation stage before the expanding foam plug is inserted into a hot hole. The hot holes were monitored for an average duration of about 5 hours, with temperature readings taken at intervals of between 10 to 30 minutes, depending on other activities on the block. More details on tests conducted on expanding foam are found in Appendix C – Foam Expander Plug **Tests**).

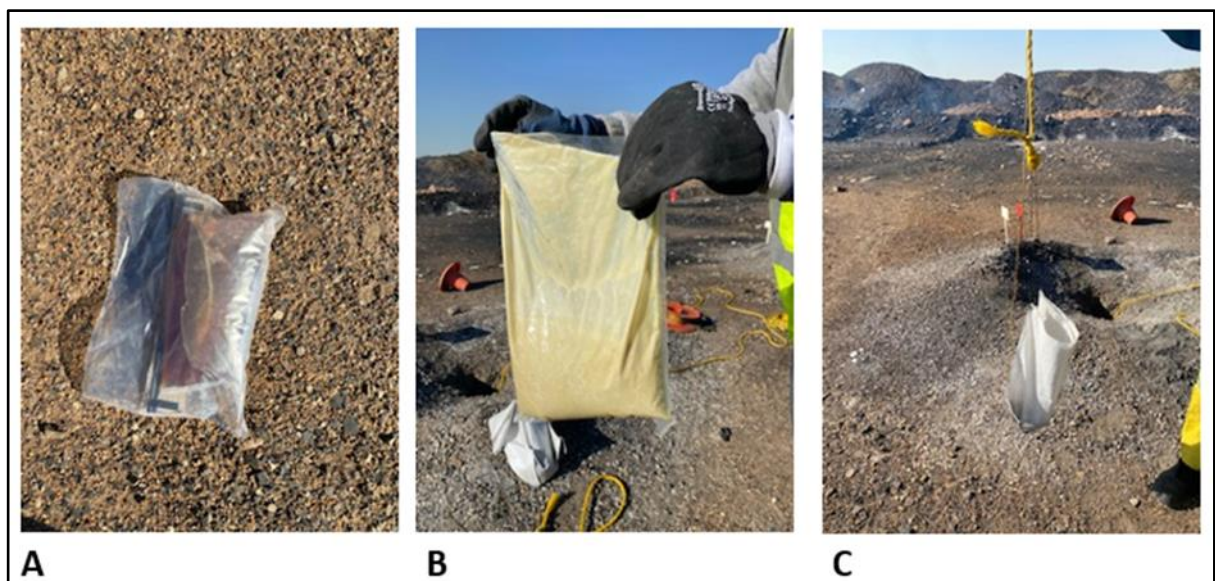


Figure 60. Foam expander plugs before mixing (A), after mixing (B) and before deployment into the hole (C)

The average difference in temperature below and above the expander foam plug for the 10 tests was calculated as 4°C (Table 21). The temperatures remained constant for the duration of monitoring as shown in Figure 61. Based on these results, it is not clear whether the expander foam plug provides any form of insulation in the hole. The difference in temperature between the position below the plug and that above the plug may be due to the fact that, if the heat source is at the bottom of the hole, the in-hole temperature generally decreases up the hole. The average expansion length of the foam plug was 0.8 m in 171 mm and 200 mm diameter holes. It should be noted though that the expansion length is dependent on the hole diameter and the presence of cracks on the sidewall of the hole. It was observed that the use of foam expander plugs to seal off holes stops venting, but when the foam is placed near the heat source, it burns, releasing white smoke, after which venting re-surfaces. Similar observations were made by the blasting teams at the host mine.

Table 21. Test results for foam bags

Test Number	Average Temperature below bag (°C)	Average Temperature above gas bag (°C)	Expansion length (m)
1	86	81	0.6
2	80	73	0.1
3	81	80	0.4
4	78	77	0.2
5	75	68	0.9
6	95	95	1.2
7	184	128	1.3
8	146	111	0.6
9	125	89	1.1
10	181	87	1.2

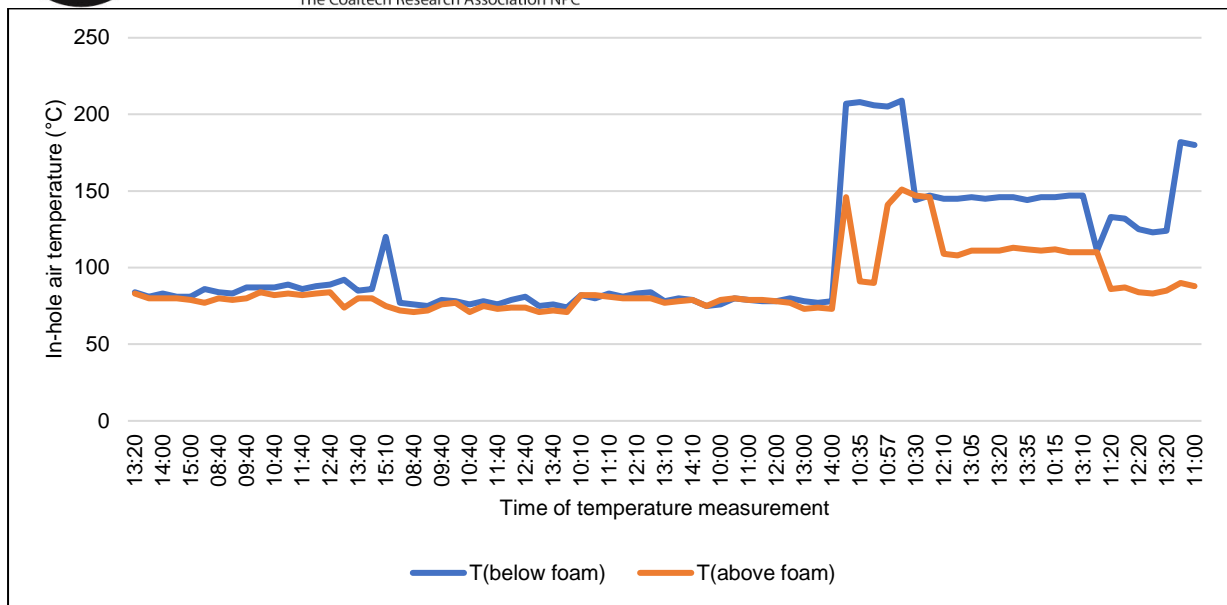


Figure 61. Temperature readings below and above the expanding foam plug for the ten tests

5.4.2 Test results on Serviplex foam plugs

The Serviplex foam plug consists of a polyurethane mixture and vermiculite, a mineral that has heat-insulating properties when heated above 300°C. Vermiculite is inert, has low heat conductivity and a low bulk density (Suvorov & Skurikhin, 2003). Figure 62 shows the preparation stage before the Serviplex foam plug is inserted into a hot hole.



Figure 62. A set up of the Serviplex foam plug before it is inserted into a test hole

Five tests on these foam plugs were conducted at the mining blocks and at the test site as shown in Table 22. The foam expanded by an average height of 1.1 m (excluding the length of the vermiculite bag). The tests had mixed results with respect to the temperature differences between the positions below and above the foam. In four of the tests, the temperature below the foam remained higher than the temperature above the foam. However, for test number 3 (Figure 63), the opposite results were found. This may have been caused by the burning of the foam in the hole, thereby leading to an increase in temperature. Alternatively, a crack in the hole located above the foam plug may have been the source of the heat. The temperature differences between the two thermocouple positions (temperature below and above the gas

bag) is greater for the Serviplex foam than for the Sibambene foam. However, it is not clear whether this was due to the effects of vermiculite or due other factors unique to the individual holes.

Table 22: Test results for Serviplex foam plug

Test Number	Average Temperature below bag (°C)	Average Temperature above gas bag (°C)	Expansion length (m)
1	97	83	1.5
2	87	74	1.4
3	84	98	0.7
4	122	77	0.9
5	148	136	1.1

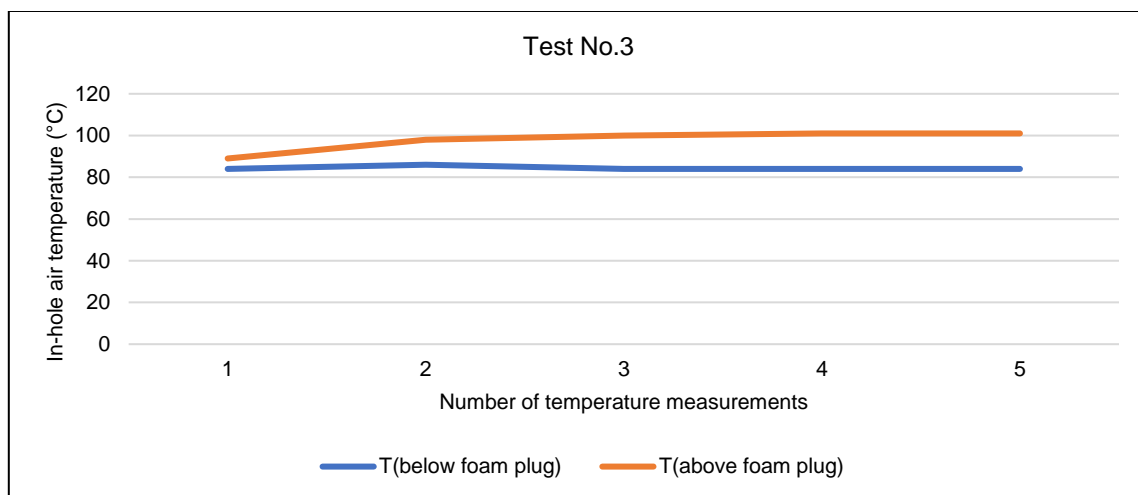


Figure 63. Results of Test No.3 of the foam plug tests

5.5 Evaluation of PVC Sleeves

The PVC sleeves tests were conducted on the mining bench at Mine A and at the Test Site 2. The four tests (Tests 1-4) conducted on the production blocks were the ideal case, with the temperature of emulsion monitored from the time of charging until just prior to setting off of a blast. In the three tests conducted at the test site (Tests 5-7), water was used in place of the emulsion, which was not available for use due to legislative and logistical reasons. The disadvantage of using water is that it has a lower boiling point than the emulsion and it does not undergo the same reaction in heat as the emulsion (release of fumes). Therefore, water does not perfectly emulate the reactions the emulsion undergoes when exposed to heat, however; it is convenient in assessing the temperature difference between inside and outside of the PVC sleeves. The PVC sleeves, at the test site were tested in holes of between 158°C and 341°C. At mining blocks, the temperature for the PVC sleeve tests were between 86°C and 99°C. This temperature of 99°C was the extreme that these PVC sleeves could be tested on a mining block based on safety and the mine procedures. For the mining block tests, temperature readings were taken every 2 minutes for a duration of up to 30 minutes using two K-Type thermocouples placed inside

and outside the PVC sleeve. A single point Blast Eye and an old version of the Multipoint Blast Eye (refer to Table 16) were used to monitor changes in the temperature of the emulsion for the tests conducted on the production block.

5.5.1 PVC sleeve tests on production blocks

Four tests on PVC sleeves, designed for use in hot holes, were conducted in holes with maximum temperatures of between 86°C and 99°C. The monitoring duration on the bench was limited by safety and production requirements stipulated in the standard operating procedures; the bench had to be evacuated promptly after charging the hot holes. Temperature readings were taken every 2 minutes. In the PVC sleeves tests, two K-type thermocouples were used to measure the temperature inside and outside the bag. For the first two tests, an older version of the Multi Blast Eye device was used to monitor changes in temperature of the emulsion. The alarm of this version of the Multi Blast Eye was set to go off when the emulsion temperature exceeded 55°C. In the other two tests, a single point Blast Eye (that gives a warning sound at 60°C and a continuous alarm at 80°C) was used to monitor the change in temperature of the emulsion.

When the explosives were loaded into the holes, the temperature as recorded by the two thermocouples, dropped. For test 1, the explosives temperature was 26.9°C. The temperature inside, T(inside), the sleeve dropped to 26°C while the temperature outside the sleeve T(outside) dropped from 84°C to 58°C as shown in Figure 64. The temperature inside the sleeve increased slightly for the duration of the test to 31°C whereas the outside temperature increased to 66°C. The difference in temperature between inside and outside of the sleeve was close to constant after loading of the emulsion at an average of 34°C.

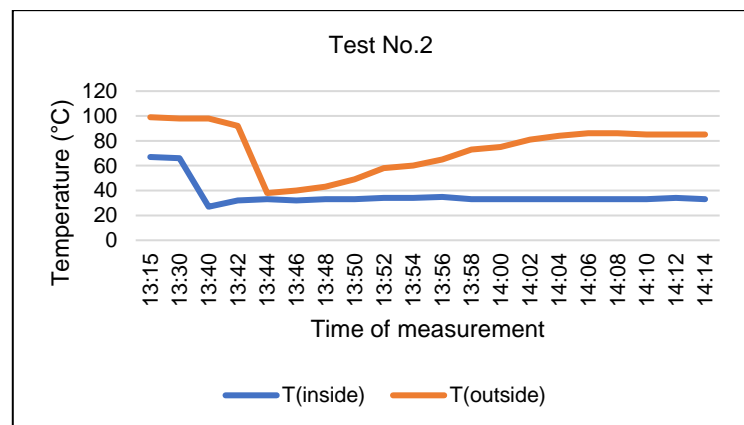
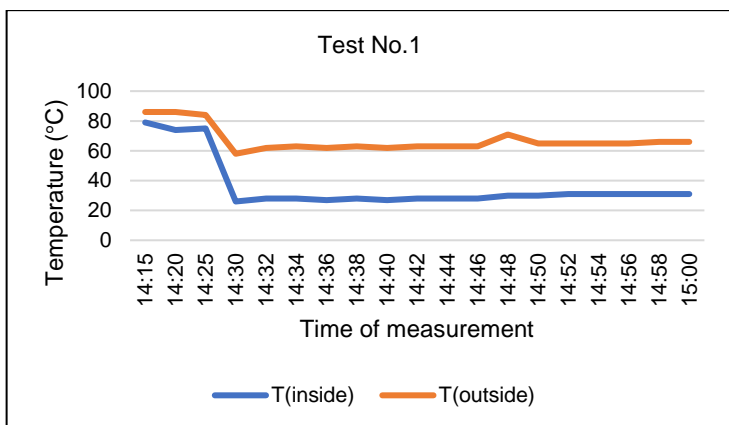


Figure 64. Temperature difference between inside and outside PVC sleeves for tests 1 and 2

Similar results were achieved for test 2, in which the temperature of the explosives was 29.2°C. The temperature inside the sleeve dropped to 68°C and then on the next reading it had dropped to 27°C. The temperature outside the sleeve dropped from 92°C to 38°C. The increase in temperature outside the PVC sleeve was more rapid for test 2 compared to test 1 as illustrated in Figure 64. It increased to 81°C within 22 minutes and remained

almost flat for the remainder of the test. The temperature (of the emulsion) inside the sleeve behaved similarly to that of test 1; the average temperature was 33°C for the duration of the experiment. During both experiments, neither the Multi Blast Eye nor the Blast Eye immersed in the emulsion inside the sleeve sounded an alarm, confirming that the temperature inside the PVC was indeed less than 60°C.

The results for PVC sleeve tests 3 and 4 were similar to those of tests 1 and 2 as shown by the temperature differences between the inside and outside the PVC sleeve in Figure 65. For these tests, the initial temperature of emulsion was 36.6°C and 38.2°C for test 3 and test 4 respectively. For PVC sleeve test 3, the variance in temperature of the emulsion and the temperature outside the PVC sleeve was an average of 46°C whereas in test 4, it was an average of 62°C.

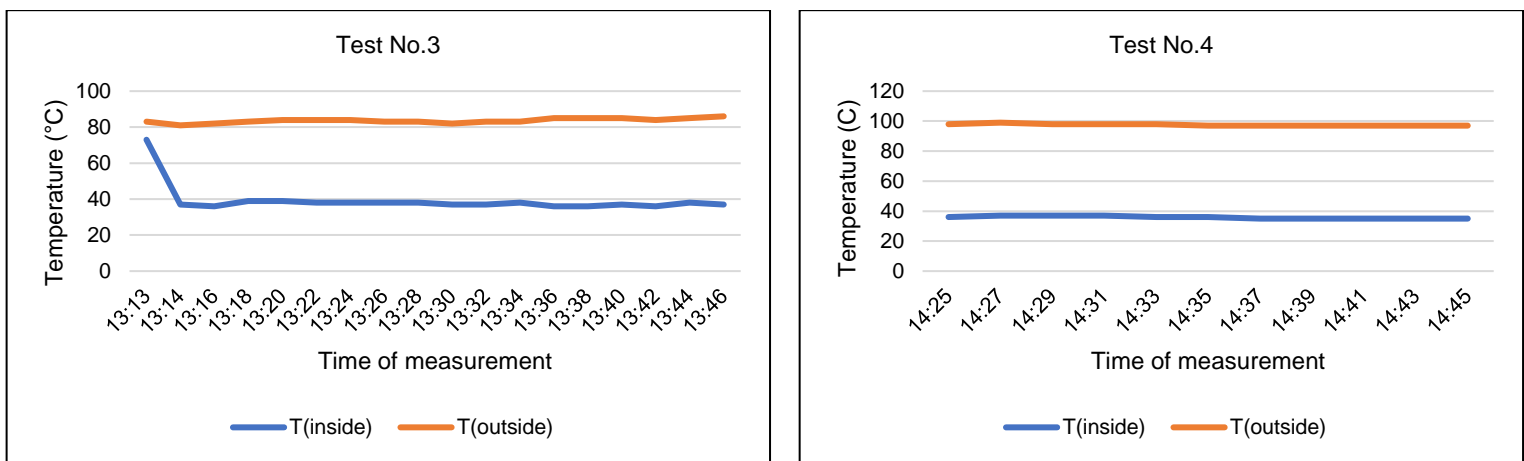


Figure 65. Temperature difference between inside and outside of PVC sleeves for tests 3 and 4 on production blocks

Based on these results, it can be said that the PVC sleeves provided some form of insulation by preventing the explosives product from gaining heat from the hot hole. The temperature difference between inside and outside the sleeve was maintained for a duration of up to 30 minutes, which was an adequate amount of time for completing charging up, tying up and the finalisation of preparing for the blast. More tests on PVC sleeves need to be conducted in various test conditions, such as in holes with higher temperatures than those in tests 1 to 4 and/or those with water. Monitoring of the tests should be done for longer periods to determine the limits at which the temperature difference between the inside and outside of the sleeve remains constant. This would assist in determining the maximum duration to be spent on a block after the charging of hot holes or, if it is deemed safe, determining the sleep time of the explosives.

5.5.2 PVC sleeves at the test site

Additional PVC sleeves tests were conducted at the test site using water in the place of emulsion. The purpose of the test was to determine the effect of PVC sleeves in preventing the gain of heat from the hole by the water. The use of water enabled the monitoring of temperature for longer periods compared to the tests conducted on

production blocks. Due to the high ambient in-hole temperatures (up to 341°C), an improvised aluminium thermocouple was used to measure the initial temperatures and the temperatures outside of the PVC sleeves. The disadvantage of this device was that the whole aluminium wire acted as a temperature sensing probe, thus, the exact location of the highest temperature could not be detected. As a result, the temperature readings from this device may not have been as accurate as those from the K-Type thermocouple, which was used to measure the temperature of the water in the PVC sleeve. **Error! Reference source not found.** shows the test setup, with water being pumped into the PVC that is suspended with wooden sticks. Figure 67 shows the retrieval and condition of a PVC sleeve from one of the holes at the test site, after a test.



Figure 66. Pumping of water into the PVC sleeve in the hole



Figure 67: Retrieval of a PVC sleeve from the hole after the test

The results for the PVC sleeve tests using water were similar to those tests in which the emulsion was used. For the three tests (Figure 68), generally, the temperature of the water, T(inside), was lower than the temperature outside the PVC sleeve for the monitoring duration. For PVC sleeve test 5, the initial temperatures inside and outside of the PVC sleeve, after the addition of water, were 64°C and 86°C respectively. Both temperatures increased slightly within 2.5 hours to about 100°C (inside) and 101°C (outside). Monitoring was paused until the following day (about 21 hours later) and temperatures were retaken. The water inside the PVC had been lost and the temperature inside the PVC sleeve was found to be 148°C and that outside the PVC sleeve was 152°C.

In PVC sleeve Test 6, the temperature of the water, inside the PVC remained constant, at an average temperature of 96.8°C for the duration of monitoring (1.75 hours). The temperature outside the PVC sleeve dropped from 300°C to 90°C during monitoring, as depicted in Figure 68. The cause of the temperature drop is not clear; however, this may have been due to the unreliability of the aluminium probe. The variance between the temperature inside and outside the sleeve also dropped from 199°C to 6°. For PVC sleeve test 7, similarly, to test 6, the temperature of the water inside the PVC sleeve remained constant at 90°C for the duration of monitoring. However, unlike in test 6, the temperature outside the PVC sleeve in test 7 remained at a fairly constant average temperature of 340°C.

The results for the tests using water indicate that the PVC sleeves provide a barrier to the transfer of heat from the hole to the water as shown by the temperature differences between the inside and outside of the PVC sleeves. Additionally, according to these results, the insulation provided by the PVC sleeves lasts for duration of up to 1 hour 40 minutes. More tests to determine the longest duration in which the temperature difference is maintained would assist in determining the duration for which activities on a block could be carried out safely after charging. However, it should be noted that water, instead of emulsion, and an aluminium probe were used for these tests.

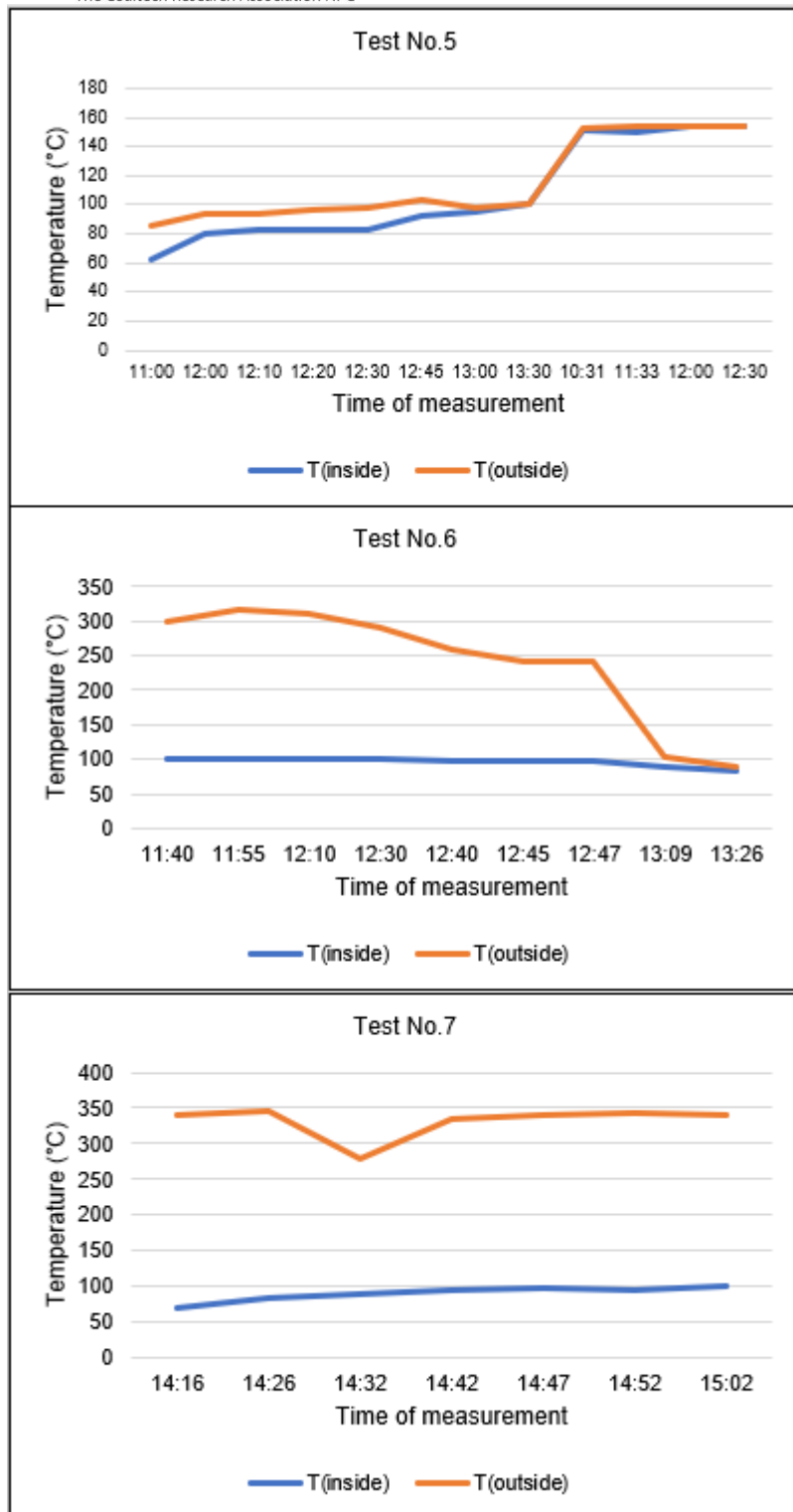


Figure 68. Temperature difference between inside and outside of PVC sleeves for tests 5 to 7 at the test site

6 Conclusion

A series of reviews, assessments and tests were conducted to understand the field of hot hole management in surface coal mines. SOPs from three surface coal mines were analysed and reviewed in detail according to specific themes in order to identify the various practices, innovations and accessories used in the management of hot holes. Visits were made to two of these mines to observe how the SOPs are implemented on actual production blocks. A fourth SOP, found in literature, was also reviewed. To gain a further understanding of the accessories used in the management of hot holes, different tests were performed at two tests sites and on production blocks at Mine A. Protocols or methodologies for conducting the tests were designed in collaboration with TOC representatives. The tests were on gas bags, expanding foam plugs, various temperature measurement and monitoring devices and PVC sleeves. Drill holes were monitored over time to determine how the ambient temperature in the holes evolves from the time the holes are drilled until prior to charging. The results and findings from these tests will contribute to the draft Best Practice Guideline for Hot Hole Management in surface coal mines, the fourth milestone of the project.

The SOP review process involved dividing the different SOPs into themes for analysis. With respect to the first theme on *alignment with regulation*, it was important for the research team to identify how a mine defines the term hot hole in comparison to the regulatory definition which states that hot hole is a shot hole, in a coal mine, *which after being drilled has an in-hole ambient temperature of 40°C or above, or shows a temperature increase of 3°C*. Furthermore, it was important to establish whether the mine SOPs satisfy the Department of Mineral Resources (2018) requirements which stipulate that at any surface mine, *“a competent person appointed by the employer in writing should measure the temperature of the shot hole in the event of a significant risk of hot holes in that environment”* and that *the temperatures of the shot holes should be measured at any point throughout the length of the shot hole and recorded prior and during charging up operation.*” Some gaps and misalignments were found in the SOPs of the four mines with respect to regulation terminology. The definition of hot holes in some of the SOPs was found to be outdated, that is, it was not based on the latest (2018) version from the DMRE. However, this did not seem to have an effect on the actual procedures in those SOPs. All the SOPs contained sections on the requirement to measure and record the temperature of holes, however, there was no explicit emphasis on fact that the in-hole ambient temperature should be measured along the depth of the hole. In all the mines, the responsibility of measuring the temperature of the holes was given to specific competent persons, depending on the complexity of the procedure.

The second SOP review theme focused on what activities are conducted during *bench preparation*, when bench preparation is conducted (on the same or different day as blasting) and who is responsible for the activities. This was key to understanding the safety measures put in place by the individual mines in preparation for a blast on hot ground, considering that there is a possibility that the in-hole temperature of drill holes changes (increases or decreases) between the time of bench preparation and charging of the holes. All the SOPs that were assessed contained sections on the need to perform some form of risk management that includes identifying, assessing and mitigating the hazards, and declaring the area safe and limiting access to the bench. These activities are vital to hot hole management. For some mines, it was not clear whether bench preparation is conducted prior to or on the day of charging. For one mine, bench preparation is a

standalone activity in the drill and blast cycle, and it is performed on the preceding day to charging. On this day, temperature measurements are taken and recorded, and are used as benchmark for further measures subsequent to charging and blasting. According to the SOPs of the different mines, specific competent persons are responsible for bench preparation.

The SOP review theme on *hot hole identification* had the purpose of establishing the methods followed in identifying hot holes and the associated accessories that are used. At one mine a pre-emptive risk assessment strategy was used to determine, in advance, whether the succeeding cut or blocks have the risks associated with hot holes. Furthermore, at this mine and in one other mine, the SOPs revealed that the risk of hot holes is mainly associated with old underground workings. This is consistent with literature and observations made during the visits to the two mines. Spontaneous combustion is referred to as a risk that is linked to hot holes in the SOPs of some of the mines. In all the SOPs, the identification of hot holes occurs between the time of drill and the time of charging. The differences lie in the frequency of measurement and recording, the classification of the holes based on the measurements and the devices used to take the temperature measurements. At one mine, it is stated in the SOP that two independent temperature measurement devices should be used. Additionally, at this mine and at the other mines, it is prescribed in the SOPs that a Blast Eye monitoring device be used after charging of the holes.

The *treatment of hot holes*, the fourth theme on the SOP review, as anticipated, was found to vary per mine depending on the hot hole classification. According to the different SOPs, those holes that are found to be in the hottest classification band are sealed off and are not charged. There is a vast difference in the temperature of the holes that may be charged or sealed off at these various mines. For example, the SOP for one mine states that holes of up to 90°C may be charged and those above this temperature may be sealed off. In contrast, at the other mine, holes that have a temperature greater than 60°C are sealed off and not charged. Different accessories are prescribed in the SOPs for use in the hot holes of varying classification. These accessories include water, cooling agents, gas bags, foam expander plugs and PVC sleeves. The procedure for the treatment of those drill holes that hole through into underground workings was found to be identical in the two mines that were visited. A procedure from one of the mines involved the sealing of these holes, at the collar, using expanding foam plugs whereas the other mine used drill chippings and/sand to seal the holes off. Other holes that were treated, according to the reviewed SOPs, are holes that vent. At one mine, a venting hole was sealed off and an adjacent second hole was drilled 2 m away and 2 m shorter than the initial hole. This procedure was based on the assumption that the source of heat and smoke was at the bottom of the hole thus, a 2 m gap would prevent venting in the latter hole. At the other mine, venting holes were sealed off with foam expander plugs and it was the responsibility of the Blasting Supervisor to ensure that these treatment processes were followed. Similarly, the responsibility of overseeing the treatment process lied with a competent person such as a Miner.

Under the fifth SOP review theme, charging and blasting of hot holes, the aim of the researchers was to understand the differences in the procedures used for hot holes (or benches) and normal holes (or benches). The review focused on the type of explosives

products used, the use of stemming material and the designation of the responsibilities for the different procedures.

At one mine, the procedures for charging and blasting were centered around working safely and promptly at those areas in which hot holes were found. This was shown by the requirement to use three explosives trucks or two trucks with rapid reload system functionality in order to reduce the time spent on charging and subsequently, the time spent by workers on the block. In addition, personnel that were either not involved in the charging or those that were not trained and appointed were removed from the block. Other safety precautions contained in the SOP include the use of explosives that contain urea or inhibitors to charge hot holes, and the charging and blasting of holes on the same day (no sleep-over holes). Detonators, which trigger at temperatures between 80°C and 110°C were not used and the drill holes were not stemmed on a blast block that has hot holes. These safety precautions were common in all the SOPs that were reviewed except for one precaution; the stemming of holes, which was practiced at one mine. Another common feature of the SOPs was the use of temperature monitoring device (the Blast Eye) to monitor the temperature of emulsion after charging the holes. Monitoring of the in-hole emulsion temperature informs the evacuation procedure; the mining block was cleared if an alarm, that was set to trigger at specific threshold temperature (80°C), reached.

Internationally, similar practices to those contained in the SOPs of local surface coal mines were identified. In Australia, a COP developed by explosives manufacturers, quoted the Australian Standard (2187.2) definition for elevated temperature as material that is above 55°C. Materials above 55°C are divided into hot ground (ground with material above 55°C but less 100°C and high temperature ground (material with a temperature of 100°C or more). In these areas, similarly to the DMRE regulations, the temperature should be measured along the length of the hole and the highest temperature measured should be recorded as the temperature for that particular hole.

On the identification of hot holes, the COP recommended that mine SOPs should contain a method that would be followed in the identification of which holes to measure, and when, and how often to test (e.g., test every hole, test every hole in a certain known hot area, test 24 hours apart to check for increasing temperature), which instruments to be used and defining the site cut-off temperatures for the mine. Similar practices, including the classification of the holes into temperature categories, were also found in the local mine SOPs. Furthermore, the selection of a measurement device with a suitable temperature range and a measuring system suitable to the conditions (for example, infra-red may not be effective in wet holes or steaming holes) is recommended by the COP. Other recommended practices to enhance safety on a block with hot holes include using specific explosives products in line with the different temperature classifications and minimising the sleep time in hot holes to prevent the heating up of explosives products which may result in premature.

Prior to conducting tests on various hot hole management accessories, protocols were developed based on past trials and the experience of personnel from the host mine. Protocols for testing temperature measurement and monitoring devices, gas bags, foam expander plugs, and PVC sleeves were designed. It should be noted that due to the different mining conditions, the protocols can be adapted by the user to accommodate factors that were not considered in these baseline versions of the protocols. Furthermore,

there are various products with vast technological innovations, therefore, the protocols were limited to aspects of already existing products or those that were available for testing.

Various temperature measurement and monitoring devices were evaluated according to the criteria developed in the test protocols. The results showed that there is no one device that is a perfect fit for the purpose of hot hole measurement and/or the monitoring of emulsion in hot holes. This is attributed to the on-going innovations and design adaptations made to these devices for the unique field of hot hole management. Additionally, in the hot hole environment, factors such as dust, water, mud and smoke impede on the optimal performance of these devices. For example, an infrared device measures the in-hole rock temperature of the hole, which is useful since it is the rock that will be in direct contact with explosives during charging, however, the accuracy of the temperatures it dictates is affected by the presence of water, dust, and smoke and its temperature range is narrower than that of thermocouples. In contrast, thermocouples measure the in-hole air temperature, which may not be a true reflection of the highest temperature in the hole. Therefore, a balance needs to be found between the strengths and weaknesses of the different devices. This may be achieved through further technological design changes to the current instruments or alternatively, as practiced in one of the host mines, the use of two distinct types of temperature measurement devices (infrared and thermocouples) to provide more reliable in-hole temperatures characteristics.

The tests conducted to understand the behaviour of holes from immediately after they are drilled until prior to charging displayed varying results. In some mining blocks, the in-hole air temperature of the majority of the holes increased (with some holes increasing by up to 40°C) over a period of three days of observation. On one mining block, the in-hole air temperature of the majority of the holes decreased overtime, however, a minority of holes increased in temperature by up to 13°C. For all the blocks, there were some holes in which the temperature remained constant, with either a decrease or increase in the in-hole air temperature of 2°C or less. The results show that within a mining block, individual holes behave differently from the time of drilling until charging. The increase in temperature in the holes is a major safety hazard and the main factor of consideration in the management of hot holes. Even though the majority of the holes on a block may display minimal temperature changes, a single hole may cause an incident due to a sudden large increase in temperature. This is the hole that may lead to the self-detonation or premature detonation of explosives on the block, resulting in accidents.

The tests conducted on two gas bag products were inconclusive due to the small sample sizes. These sample sizes were limited by the availability of the gas bags at the mine. A larger sample size was used for the tests on the most commonly used gas bag at the host mine. The results suggested that Gas Bag 1 did not last for a period of 24 hours or longer in a hot hole of temperatures greater than 43°C. The gas bags failed by either deflating or rupturing. Thus, the use of these gas bags, overnight, as a solid base for emulsion in *bhoboza* holes or to seal off the bottom of venting holes is not recommended. However, it is noteworthy that a larger sample size may have resulted in a different outcome. Additionally, tests to determine how much weight the gas bags can carry were not conducted.

Tests conducted on expanding foam and observations made at the mining blocks revealed that venting of holes is indeed stopped by the use of expanding foam plugs. However, when the foam is placed near the heat source in the hole, it burns, releasing white smoke,

after which venting re-surfaces. Thus, the use of expanding form, as a solid base for emulsion in bhoboza holes or to seal off the bottom of venting holes is not recommended. The foam plugs that were tested expanded by between 0.4 m and 1.2 m in the holes.

The PVC sleeve test results indicated that the PVC sleeves provided some form of insulation that prevented the explosives product (and water) from gaining heat from the surrounding hot hole walls. The temperature variance inside and outside the sleeve was maintained for a duration of up to 30 minutes in the emulsion tests, which was an adequate amount of time for completing the charging up and tying up processes in preparation for a blast. This duration was longer (more than 1.5 hours) in the tests conducted with the use of water. More tests on PVC sleeves need to be conducted in various test conditions, for example in those hot holes that have water and for longer periods to determine the limits at which the temperature difference between the inside and outside of the sleeve remains constant. This would assist in determining the safe maximum duration to be spent on a block after the charging of hot holes or, if it is deemed safe, determining the sleep time of the explosives in those holes of less extreme temperatures.

7 Recommendations

SOPs

SOPs of a mine should be drafted collaboratively, including inputs from the following stakeholders:

- Drilling teams – these are the first people to be exposed to a hot hole. The observations they make and the data that they collect would be vital for inclusion into the procedures for handling hot holes.
- Blasting team – this team works in close proximity with the drilling team and there is information sharing between the two teams. In addition, this team is involved in the implementation of the procedures on a daily basis. Their contribution to SOPs would be invaluable.
- Relevant temperature measurement and monitoring device manufacturers – these manufacturers should be involved in the process (of handling hot holes) to provide the technical knowledge of the devices that would be used by the drilling and blasting teams. This would also assist the manufacturers in improving the designs of the devices, thus tailoring the device to the real environment requirements.
- Manufacturers of explosives and accessories – these manufacturers supply products that come into direct contact with the hot holes. Their technical knowledge should not be used in isolation but, collaboratively to prevent unforeseen events arising from the use of their products in hot hole environments.
- Manufacturers of hot hole management accessories (gas bags, foam plugs, PVC sleeves etc...) – these manufacturers provide the accessories used to reduce the risk associated with hot hole environments. Their inputs in the correct use of the products they supply is invaluable for SOPs.
- The regulator – the requirements of the regulation are understood differently by various stakeholders. There should be clarity on the terms, definitions and limits used in the regulation so that they are interpreted correctly in the SOPs.

The following is recommended for incorporation into the SOPs for different mines:

- Definitions – clear definitions of hot holes, that align with the current DMRE regulations, and the associated temperature classifications or ranges
- Hot hole measurement and monitoring – clarity on what instruments should be used and by whom, how the instruments should be used to avoid incorrect readings, when and how often the instruments should be used. Information on what is being measured (the in-hole air temperature or the in-hole rock temperature) should also be clearly specified.

Temperature Measurement and Monitoring Devices

The following is recommended for the selection and use of temperature measurement and monitoring devices:

- Mines to advise manufactures to consider further technological design changes on both temperature measurement and monitoring devices to ensure that they function provide accurate results in the presence of water, dust, and smoke. These devices should also be user-friendly to avoid their abuse and incorrect use, which would defeat the purpose of enhancing safety.

- Mines should consider using temperature measurement devices that measure the in-hole rock temperature and/or (depending on practicality and affordability) the in-hole air temperature to gain a better understanding of the rock and air temperature separately. For instance, it is the rock that comes into direct contact with the explosives and hot hole management accessories. Knowing its temperature would assist in determining the limitations of the products.
- Temperature measuring devices selected should ideally produce a profile of temperatures along the depth of the hole. This way the production team will get a clear indication of the position of the heat source, in instances where it is not at the bottom of the hole.
- Temperature monitoring devices selected should be audible in the presence of explosives trucks during charging.

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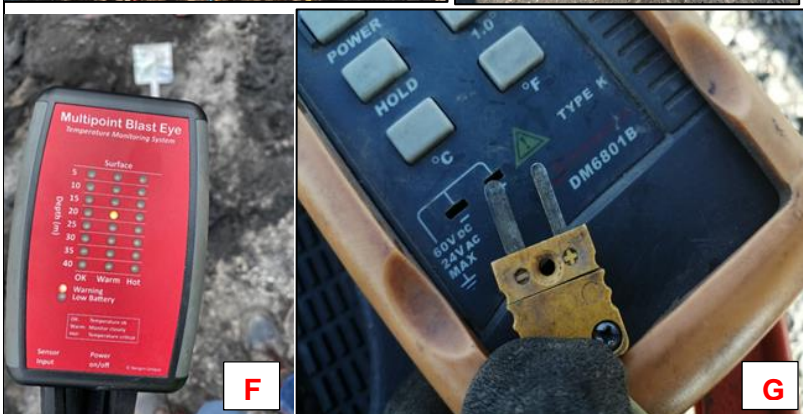
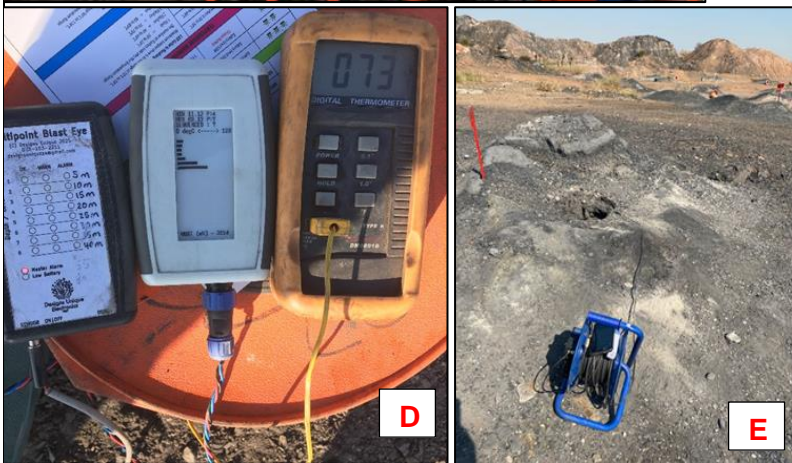
Appendix A – Tests on temperature measurement and monitoring devices



The image shows calibration of the Blast Hole Temperature Logger (infrared device). This is a daily activity conducted by the Blaster to ensure the measurement of accurate readings.



The image shows calibration (and testing) of the PositioNXT HHMS and the Ninggi Safeblast using boiling water.



These images show some of the tests and temperature readings from the various temperature measurement and monitoring devices.

A – The maximum in-hole temperature (bottom of the hole), displayed on the K-Type multimeter (left) measured by a thermocouple, was 84°C. For the same hole, the HHMS (right) measured the maximum in-hole temperature as 81°C and this temperature corresponded with the farthest sensor (bottom of the hole) along the temperature wire.

B – An image of the QMR Temperature Log. The QMR app that logs the temperatures can be seen on the mobile phone. A reel with the temperature wire and a portable power source are also visible on the image.

C – In this image, the maximum in-hole air temperature measured by the K-Type thermocouple and the HHMS are both 67°C. The maximum in-hole rock temperature, measured by the Blast Hole Temperature Logger (infrared device) was 51°C.

D – The image shows the K-Type thermocouple and the HHMS with in-hole air temperature readings of 73°C and 69°C respectively. The old version of the Multi-Point Blast Eye (far left) is also shown in the image with a red light signalling that an alarm was triggered (above 55°C). The light that corresponds with the sensor that triggered the alarm is not visible.

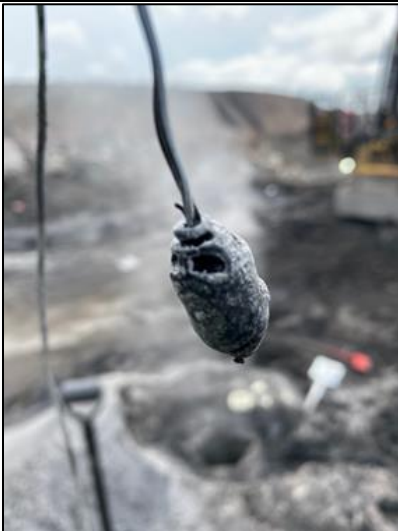
E – The set-up of the QMR Temperature Logger in a hot hole at Test Site 1.

F – The output display unit of the Multi-Point Blast Eye. In this instance the orange light corresponds with the sensor located 20 m deep (at the bottom of the hole), meaning that the temperature of the hole was greater than 60°C but less than 80°C.

G – The K-Type thermocouple wire connects to the digital thermometer via the yellow connector. The



The image shows the temperature wire of the of the PositionNXT HHMS. As discussed in section 5.1, the sensors/chips are not covered in any type of insulation. This may assist in the quick detection of the in-hole air temperature, however, the sensors are exposed to the direct heat, mud and water, which may reduce the accuracy of the temperature readings.



The image shows the temperature wire and sensor in of the Multi-point Blast Eye (Mk2). The wire end that connects to the bottom of the wire (and is used to hold a sinker/weight) melted off in a hole.

Table 23. Calibration of the Ningi Safeblast with boiling water

Wire	Wire length	1 - Did not have a sound	2	3	4	5
1		No "ok" sound , No light when in water	No "ok" sound , No light when in water	No "ok" sound , No light when in water	No "ok" sound , No light when in water	No "ok" sound , No light when in water
2		Initially works, No "ok" sound, No lights on both outside and inside water.	Initially works, No "ok" sound, No lights on both outside and inside water.	Initially works, No "ok" sound, No lights on both outside and inside water.	Initially works, No "ok" sound, No lights on both outside and inside water.	Initially works, No "ok" sound, No lights on both outside and inside water.
3		No "ok" sound and No lights both outside and outside water	No "ok" sound and No lights both outside and outside water	No "ok" sound and No lights both outside and outside water	No "ok" sound and No lights both outside and outside water	No "ok" sound and No lights both outside and outside water

		and outside water				
15		Initially worked (green light up to 15m), No LED and No sound inside water, Orange LED light up to 15m outside water	Initially worked (green light up to 15m), No LED and No sound inside water, Orange LED light and sound up to 15m outside water	Initially worked (green light up to 15m), No LED and No sound inside water, Orange LED light and sound up to 15m outside water	Initially worked (green light up to 15m), No LED and No sound inside water, Orange LED light and sound up to 15m outside water	Initially worked (green light up to 15m), No LED and No sound inside water, Orange LED light and sound up to 15m outside water
16		Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)
17		Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)	Initially worked (green light up to 30m), No LED light and sound inside water, Green LED light and sound outside water (for a few minutes)

Appendix B – Gas Bag Tests

	<p>The image shows a set-up of the gas bag test showing 3 K-Type thermocouples (wrapped around the orange reels) inserted into a hot hole.</p>
	<p>In the image, a deflated gas bag was retrieved from a hole. A K-Type thermocouple wire had been tied to the gas bag to measure the temperature on the bag.</p>
	<p>The gas bags had different failure mechanisms. In some tests (left), the gas bags ruptured/burst whereas in other tests (right), the gas bags failed due to puncturing by sharp hot rock from the side wall of a hole.</p>

Appendix C – Foam Expander Plug Tests



The image shows a different product/solution for the sealing holes. The vermiculite bag is dropped into the hole before the polyurethane mixture is dropped on top. The idea is to use vermiculite as a layer of insulation.