Development of Best Practice Guideline for the management of hot holes in surface coal mines

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Abstract

Surface coal operations in which mining activities are conducted above old underground workings experience hot holes after drilling. In a coal mine, hot holes are defined as shot holes, 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. Hot holes and other cavities, such as cracks, pose health and safety risks to workers, such as exposure to hot air and high concentrations of noxious gases released from these holes. In addition, workers may be exposed to premature detonation of explosives caused by in-hole temperature increases and chemical reactions. To this end, Coaltech Research Association commissioned a project to develop a Best Practice Guideline for the management of hot holes. This paper is a compilation of the activities conducted in the development of the Best Practice Guideline between 2021 and 2022. The activities included a review of standard operating procedures and hot-hole temperature-measuring and -monitoring devices, and the assessment of current hot-hole procedures at selected mines. The results indicated that management of hot holes requires a focus on pre-emptive risk assessment of mining blocks, identification of hot holes using the correct temperature-measuring devices, and continuous monitoring of hot holes from the time of drilling until just before blasting. Hot-hole management accessories, such as polyvinyl chloride sleeves, were found to be effective in insulating the hot-hole emulsion from the rock mass temperature, thus preventing the potential for premature detonation.

Keywords

hot hole, hot-hole management, in-hole temperature, temperature-measuring device, temperature-monitoring device, premature detonation

Introduction

Surface coal mining activities that occur above old underground workings present the risk of intercepting hot ground or underground fires through cavities, such as deep cracks and sinkholes in the ground, and by the drilling of blast holes. In such mining areas, lower coal seams were mined first through underground mining methods in the past and the upper coal seams are currently being mined using surface mining methods, hence the occurrence of these cavities. The cavities provide ingress for oxygen and an outlet for noxious gases and heat generated by spontaneous combustion in the previous underground bord-and-pillar coal mines (Sloss, 2015). When air seeps through cracks on the ground or through blast holes and encounters coal, oxidation occurs. Oxidation is an exothermic reaction, in which heat is released. Because the heat is trapped in underground workings, it leads to a constant increase in the temperature of the rock mass. The magnitude of coal oxidation increases with an increase in the surface area of the coal that is exposed to air; thus, more hot holes are found when drilling on the coal seam than when drilling on overburden. Loading of explosives under such high temperatures is a dangerous process that can cause premature detonation or failure of explosives and initiating systems.

The other source of the heat found in hot holes, not covered in this study, is reactive ground. The term reactive ground refers to ground that contains mainly iron and copper sulfides and, to a lesser extent, coal sulfides. This ground undergoes a spontaneous exothermic reaction when it encounters nitrates of ammonium, calcium, and sodium (found in explosives products). The reaction involves chemical oxidation of the sulfides, resulting in the release of heat (Sharma, 2010; White, 2018; AEISG, 2020).

Figure 1 illustrates the processes involved in the generation of underground heat and fires when mining over old underground workings.

Considering the risks associated with hot holes and their effects on people, equipment, and infrastructure, Coaltech Research Association commissioned a project to develop a Best Practice Guideline (BPG) for the management of hot holes.

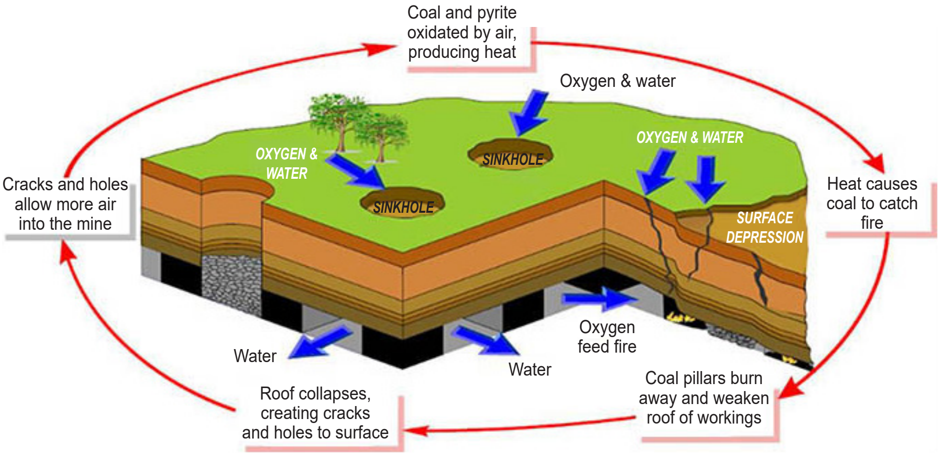

Figure 1—Cycle of processes that occur when mining over old underground workings (Tose, 2022)

Previous research by authors that include Eroglu et al. (1999), Eroglu (2003), Otter et al. (2005), Uludag (2007), Phillips et al. (2011), Sloss (2015), Genc and Cook (2015), Oageng (2016), Onafide and Genc (2019), and Ngwenyama and de Graaf (2021) extensively describes spontaneous combustion. Their work covered a wide scope of spontaneous combustion aspects that include the causes, prevention, prediction, and monitoring of spontaneous combustion on different mine areas. In addition, the previous research applies to varying spontaneous combustion sources, such as spoil dumps, coal stockpiles, underground coal mining faces, goaf zones of longwall mining methods, open pit highwalls, and, to a lesser extent, on drill holes on benches. However, the concepts for managing spontaneous combustion are similar and relevant to the concepts for the management of hot holes in surface mines located over old underground workings. These concepts include solutions such as the use of sealing agents to minimize the time a coal surface is exposed to air, thus preventing spontaneous combustion. Similarly, for the management of hot holes, the holes are sealed at the collar with a cone or sealing agent, such as an expanding foam, to prevent the ingress of air into the bottom of the hole. Another example is the practice of 'just-in-time drilling', which ensures that newly uncovered coal is drilled, blasted, and immediately excavated after exposure to the air. This is similar to the hot-hole management practice of charging, tying up, and blasting as soon as drilling is completed to minimize the time spent time on the block (Eroglu, 2003; Phillips, et al., 2011; Sloss, 2015; Ngwenyama and de Graaf, 2021).

Other research related to the management of hot holes has been conducted by explosives manufacturing companies, such as African Explosives and Chemical Industries (AECI) and Bulk Mining Explosives (BME). Rorke and Conradie (2018) reported on small-scale tests, carried out by BME, to characterize the behaviour of two explosive product types at high temperatures (up to 750°C). The tests showed the reactions undergone by the products and the associated temperatures; for example, the boiling point of the emulsion was determined to be 150°C and heat generation (or the occurrence of an event) started at 320°C. Rorke and Conradie concluded that the risk of premature detonation in hot holes is likely to be caused by charging accessories, such as initiators, that are sensitive to detonation above 80°C. Tose (2018; 2022) reported on small- and large-scale tests conducted by AECI to investigate the behaviour of explosives in hot environments. The tests enabled the determination of temperatures at which:

- grey-white fumes start to form (110°C);
- emulsion product is ejected (140°C–220°C);
- brown fumes are released (180°C);
- detonation/ deflagration occurs (220°C–260°C).

The Department of Minerals Resources and Energy (DMRE) defines hot holes 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 (Department of Mineral Resources, 2015; Mine Health and Safety Council, 2019). Working in such environments may expose workers to hazards such as (AEISG, 2020; Tose, 2022):

- hot air exhausted from underground;
- high concentration of noxious gases, such as carbon dioxide, carbon monoxide, and sulfur dioxide;
- premature detonation due to:
  - temperature increase, which affects the chemical composition of explosives products;
  - softening and/or melting of initiating system components.

Figure 2(a) and (b) illustrate hot holes that are venting; Figure 2(c) shows a hot hole with fire at its bottom.

Figure 2—(a, b) Venting holes and (c) a fire in a hot hole at a mine that has hot-hole challenges

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 explosive products, causing suboptimal blasts. Mining on 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 to mitigate all associated risks. Chapter 4.16(5) of the Mine Health and Safety Act (1996) mandates that an employer, in consultation with the explosives manufacturer or supplier, must prepare and implement a procedure to prevent persons from being exposed to the significant risks associated with hot holes. South African coal mines affected by these risks have implemented such procedures; however, as shown in Table I, incidents related to hot holes and/or reactive ground continue to occur. The causes of such incidents include limited site-specific knowledge on the interaction between a hot hole and explosives products, explosives accessories, and hot-hole management instruments, limited knowledge about the temperature profile along the entire length of a shot hole, and, in some cases, lack of compliance with procedures. These factors contributed to the need for developing a BPG that would assist to mitigate the risks associated with hot holes.

It is difficult to determine whether a drill hole is hot or not by just observing it from the surface. There are indicators, such as venting or smoking of the holes, that are sometimes used to identify a hot hole (Rorke & Conradie, 2018; AEISG, 2020). However, the indicators obtained from this technique do not provide adequate information, such as the exact temperature of the holes, that would allow 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 (Anthony and Grobbelaar, 2009). Temperature-measuring and -monitoring 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 vary according to the method for which they are designed to be used in detecting the temperature (AEISG, 2020). The methods of detection include:

- in-hole air temperature measurement;
- in-hole rock surface temperature measurement;
- non-in-hole/surface temperature measurement devices.

Table I

Examples of local and international incidents caused by hot holes and/or reactive ground (adapted and modified 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, one fatality
2018	South Africa	Uncontrolled detonation of two blast holes caused by an extreme hot hole
2016	Indonesia	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, one fatality

Explosive temperature-monitoring devices are disposable devices designed for use during charging to monitor the temperature change of emulsion (Australasian Explosives Industry Safety Group, 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, 80°C, 95°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 emulsion temperature during charging. Anthony and Grobbelaar (2009) developed and tested a probe recording-monitoring system that continuously monitored the temperature and pressure when explosives were loaded into hot holes. The system consisted of three temperature probes and two pressure transducers, a monitoring station, and a recording station located at a safe distance from the hot holes. The tests assisted in determining the different temperatures at which emulsion reacts in a hot hole, such as the emission of nitrous gases, which the authors correlated with a drop in temperature. The tests also showed that the temperature along the profile of a hot hole is not necessarily equal to the temperature at the bottom of the hole.

While Anthony and Grobbelaar (2009) used temperature probes to measure the temperature of hot holes, there are various other types of temperature-measurement and -monitoring instruments that 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, use of the device should not impede productivity on the bench.

Methodology

Development of the BPG adopted elements of both qualitative and quantitative research, usually called mixed research methods. A qualitative research approach is exploratory and seeks to gain a deep understanding of a problem, as explained by Creswell and Creswell (2018). This approach helped to investigate the subject of hot holes, ensuring that independent thoughts of mining stakeholders and their in-depth understanding of the subject was captured. The qualitative aspects included a review of standard operating procedures (SOPs), hot-hole temperature-measuring and -monitoring devices used locally and internationally, monitoring and observing current hot-hole procedures at selected mines, and assessing the effectiveness of various hot-hole management accessories, such as gas bags and polyvinyl chloride (PVC) sleeves (Figure 3). These documents and apparatus were used by the various mines at the time of the projection execution between 2021 and 2022.

Quantitative aspects of the methodology involved collection of temperature data using different types of temperature-measuring devices during various experiments conducted with the different hot-hole management accessories. Further details on the methodology and the protocols for the tests can be accessed on the BPG report found on the Coaltech Research Association website (Coaltech Research Association, 2022). The data were analysed, and the generated insights were integrated with the results from the qualitative research to develop the BPG. Two study mines were selected based on the existence of hot-hole risk in their operations and the presence of controls implemented to prevent, reduce, and/or eliminate the risk.

It is noteworthy that, for each experiment, a specific protocol or methodology was designed and used. Similarly, for evaluating the performance of the different types of temperature-measuring and -monitoring devices, assessment criteria were developed, as shown in Table II.

Results and discussion

Results from SOP reviews, the evaluation of temperature-measuring and -monitoring devices, the behaviour of hot holes from drilling to charging, and from the tests on hot-hole management devices are discussed in this section. It should be noted that these results are based on the SOP versions that were used by the various mines during the time of the project between 2021 and 2022.

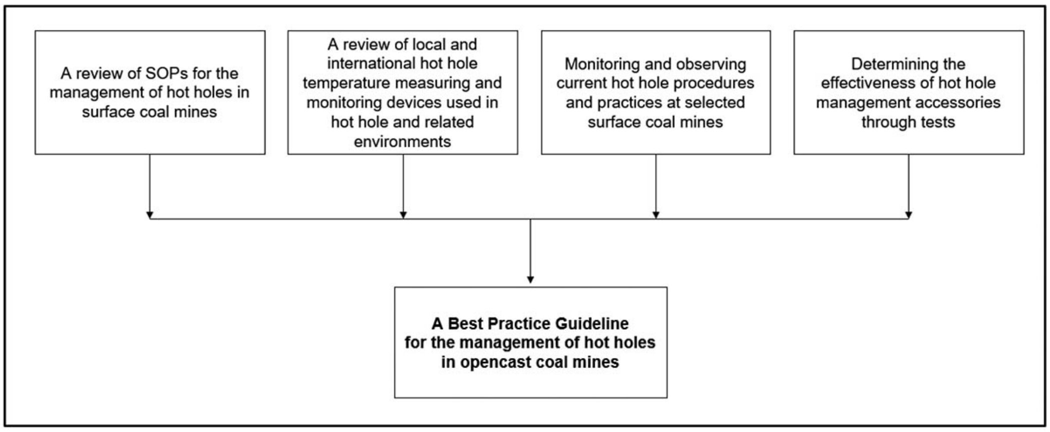

Figure 3—Contents of the research methodology followed in the development of the Best Practice Guideline

Table II

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 visible display of the control system output (monitor, LCD screen, LED, 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 clearly heard 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.

Review of Standard Operating Procedures

The SOP review process involved collating and reviewing SOPs from three South African coal mines (Mine A, Mine B, and Mine C) owned by three different mining companies and a Code of Practice (COP) from the Australian mining industry. In the review process, SOP contents were categorized into five themes for analysis. The themes are in alignment with regulation; risk assessment; identification of hot holes; treatment of hot holes, and hot-hole charging and blasting.

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 with the regulatory definition, which states that a 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 SOP satisfied the DMRE's definition found in Mine Health and Safety Council (2019) 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 three mines with respect to regulation terminology. The definition of hot holes in some SOPs was not in alignment with the latest (2018) definition provided by the DMRE. However, this did not seem to influence the actual procedures for managing hot holes in those SOPs. All SOPs reviewed contained sections on the requirement to measure and record the temperature of holes. However, there was no explicit emphasis on the importance of measuring the in-hole ambient temperature along the depth of the hole. In all SOPs from the different mines that were reviewed, the responsibility for measuring the temperature of the holes was given to specific competent persons, depending on the complexity of the procedure.

The second SOP review theme, *risk assessment*, 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 SOPs that were assessed contained sections on the need to perform some form of a risk assessment that includes identifying hazards, declaring the area safe, and limiting access to the bench. These activities are vital to hot-hole management. For Mine B and Mine C, it was not clear whether bench preparation is conducted prior to or on the day of charging. For Mine A, bench preparation is a standalone activity in the drill-and-blast cycle and is performed on the preceding day to charging. On this day, temperature measurements are taken and recorded, and are used as benchmark for further measurements after 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 Mine A, a pre-emptive risk assessment strategy is used to determine, in advance, whether the succeeding cut or blocks have risks associated with hot holes. Furthermore, at Mine A and Mine B, 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 selected 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 SOPs, identification of hot holes occurs between the time of drilling 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 Mine A, it is stated in the SOP that two independent temperature measurement devices should be used. Additionally, at this mine and at Mine C, it is prescribed in the SOP 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, holes that are found to be in the hottest classification band are sealed off and 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 Mine A states that holes of up to 90°C may be charged and those above this temperature should be sealed off. In contrast, at Mine B, 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 hot holes of varying classifications. These accessories include water, cooling agents, gas bags, foam expander plugs, and PVC sleeves. The procedure for the treatment of drill holes that hole through into underground workings was found to be identical in the two mines that were visited. A procedure from Mine A involves the sealing of these holes at the collar, using expanding foam plugs, whereas Mine B uses drill chippings and/or sand to seal the holes off. Other holes that are treated, according to the reviewed SOPs, are holes that vent. At Mine B, a venting hole is sealed off and an adjacent second hole is drilled 1 m away and 2 m shorter than the initial hole. This procedure is based on the assumption that the source of heat and smoke is at the bottom of the hole; thus, a 2 m gap would prevent venting in the adjacent hole. At Mine A, venting holes are sealed off with foam expander plugs and it is the responsibility of the Blasting Supervisor to ensure that these treatment processes are followed. Similarly at other mines, the responsibility of overseeing the treatment process lies with a competent person, such as a Miner.

Under the fifth SOP review theme, *charging and blasting of hot holes*, the aim of the research 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 Mine A, the procedures for charging and blasting are centred 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 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 to reduce the number of people exposed to the risk. Other safety precautions contained in the SOPs 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 that 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 SOPs that were reviewed except for one precaution: the stemming of holes, which is practiced at Mine B and Mine C. Another common feature of the SOPs is the use of a temperature-monitoring device (the Blast Eye) to monitor the temperature of bulk/emulsion after charging the holes. Monitoring of the in-hole emulsion temperature informs the evacuation procedure: the mining block is cleared if an alarm, which is set to trigger at specific threshold temperature (e.g., 80°C), is 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 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, similar to the DMRE regulations, the temperature should be measured along the length of the hole and the highest measured temperature should be recorded as the temperature of that particular hole.

On the identification of hot holes, the COP recommends that mine SOPs should contain a method that would be followed in the identification of which holes to measure, when and how often to measure them (e.g., test every hole, test every hole in a certain known hot area, test 24 h apart to check for increasing temperatures), which instruments to use, 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 (e.g., infrared 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 of hot holes that are loaded with explosives. The sleep time, which is the time that explosives are left loaded in hot holes, is an important factor to consider in preventing heating up of explosives products, which may result in premature detonation.

Evaluation of temperature-monitoring and -measuring devices

Various temperature-measurement and -monitoring devices, including the Blast Eye (Figure 4(a)), 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 temperature in hot holes. This is attributed to the ongoing 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 the optimal performance of these devices. For example, an infrared device (Figure 4(b)) measures the in-hole rock temperature, which is useful because it is the rock that will be in direct contact with explosives during charging; however, the accuracy of the temperatures it measures is affected by the presence of water, dust, and smoke, and its temperature range is narrower than that of thermocouples. In contrast, thermocouples (Figure 4(c) and (d)) 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 temperature characteristics.

Field test results

The tests conducted to understand the behaviour of holes, from immediately after drilling until prior to charging, displayed varying results. In some mining blocks, the in-hole air temperature of most 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 over time; however, a minority of holes increased in temperature by up to 13°C. For all 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 most 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 self-detonation or premature detonation of explosives on the block.

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 of 20 hot holes was used for the tests on the most commonly used gas bag at the host mine. The results suggested that these gas bags do not last for a period of 24 h 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

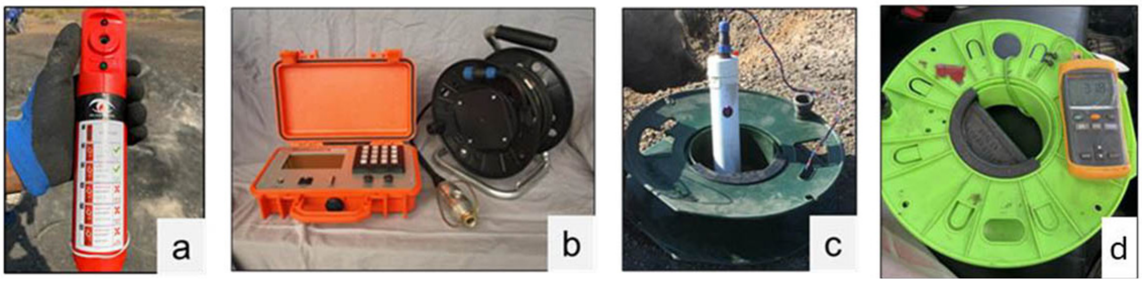

Figure 4—Examples of various temperature measurement and monitoring devices. (a) Blast Eye, (b) infrared, (c) and (d) thermocouples

holes that breakthrough to underground workings (also known as *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. As a recommendation, future tests to determine how much weight the gas bags can carry should be conducted.

Tests conducted on expanding foam and observations made at the mining blocks revealed that venting of holes is indeed stopped when using 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.

Summary of the Best Practice Guideline

The BPG was compiled from literature, experimental results, and engagements with mining industry stakeholders. The full Guideline can be accessed on the Coaltech Research Association website (Coaltech Research Association, 2022). The Guideline covers hot-hole management aspects such as risk assessment, the identification of hot holes, the treatment of hot holes, and the

Table III

Summary of Best Practice Guideline contents

Mining process stage	BPG stage	Risk management activities
Before drill and blast activities	Pre-emptive risk assessment	• Classify mining blocks according to their potential to have hot holes (e.g., those over old mining workings). • Classify the mining blocks into hot and normal blocks and according to the risk assessment matrix of the operation. • Develop broad risk mitigation strategies for managing the normal and hot blocks, including the type of explosives product and accessories and hot-hole management tools to be used. • Develop focused risk mitigation strategies for managing holes of different temperature on the same block, including the types and quantities of explosives products and accessories and hot-hole management tools to be used.
After drilling	Identification of hot holes	• Measure the initial temperature of the holes on a block using the appropriate temperature-measuring device. • Record the measured temperatures on a data sheet and on hole identifiers, such as plant markers, tags, or flags. • Record other information, including 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. • Classify the holes on a block according to their temperature into categories such as cool/normal, hot, or very/extremely hot. • Mark the holes with an identifier, such as a tag or flag, that is visible to all workers on the block. • Perform hot-hole treatment where applicable and as per the risk assessment of the mine. • Seal off those hot holes that will not be charged as per the risk assessment of the mine.
During charging	Hot-hole charging and blasting	• Re-measure the temperature of the holes on the block just prior to charging • Record the measured temperature on a data sheet and on the tag or flag. • Assess the temperature measurement to identify whether it still falls within the correct temperature class. • If the temperature of the hole has increased and it now falls within a new class, re-classify the hole and blast block accordingly. • Perform hot-hole treatment where applicable and as per the risk assessment of the mine. • In all the holes classified as hot holes, insert the appropriate temperature-monitoring device to monitor temperature change of the hot-hole-specific explosives product. • Load the holes with hot-hole-specific explosives product as per the suppliers' recommendations. • Monitor the hot -hole monitoring device for any alarms that may be triggered due to an increase in the temperature of the hot-hole explosive product. • Monitor the hot holes for any signs of smoke or fumes, as these indicate that the explosives product is heating up.

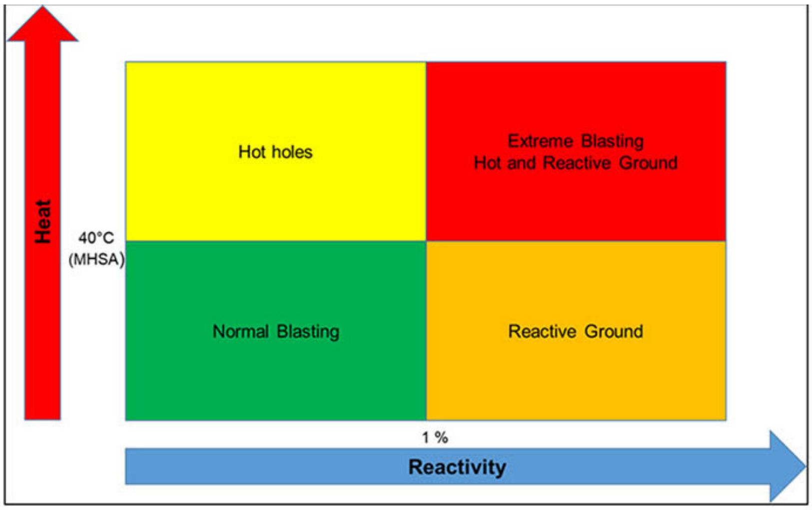

Figure 5—Various mine site conditions for the selection of explosives products (AEISG, 2020; Tose, 2022)

associated charging and blasting practices. A summary of the main contents of the BPG for the management of hot holes is shown in Table III.

Drilling and blasting activities of the mining cycle should be preceded by a pre-emptive risk assessment to identify the risks associated with hot holes and devise associated mitigating measures. Such an assessment should result in the classification of mining blocks according to the varying risk; for example, mining blocks located over old underground workings would carry a higher risk of hot holes than other mining blocks. This would enable the selection of appropriate site-specific hot-hole management tools, explosives products, and any other relevant charging and blasting accessories ahead of time. The selection of explosives products and accessories for use in hot-hole environments should be informed by the mine site conditions (Figure 5) and the associated risk assessments. Additionally, large-scale tests on the explosive products should be conducted at the mining sites. These tests assist decision makers in identifying the full spectrum of risk associated with blasting in such environments by utilizing 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.

After holes have been drilled on the mining blocks, it is important that the temperature is measured using the appropriate temperature-measuring device. Such a device should accurately measure the in-hole rock surface temperature and/or in-hole ambient temperature, enable multi-point temperature detection or temperature measurement along the hole length, and be durable so that it can function in rugged environments containing dust, water, and mud. Furthermore, the use of the temperature-measuring device should not decrease the productivity of workers. Thus, the time to set it up and record the temperature in a hole should be less than two minutes, considering that a block may contain over 100 holes. The measured hole temperatures should be recorded on data sheets and on identifiers, such as tags or flags, that would be placed on the crest of a hole. Ideally, the temperature measurements would be digitally captured and communicated to the relevant authorities in real- or near real-time for quick updates to the risk assessments and blast designs.

Unexpected operational constraints may deem it impossible to drill, charge, and blast on the same day, leading to changes (increase or decrease) in the temperature of the holes on a block. Therefore, further temperature measurements should be taken on the day of charging and blasting so that the blast design and risk assessment are accordingly updated. For example, an increase in the temperature of a hole may result in re-classification of the hole from a normal hole to a hot hole, which would affect how it is managed or charged. The risk associated with hot holes is high during the charging process; therefore, all activities that occur during this process should be completed safely and promptly. In addition to re-measuring the temperature of the holes before charging commences, other activities that should be performed include monitoring the temperature of hot-hole explosives products and continuously assessing the holes to identify any developing hazards. Moreover, a loading sequence that enables a quick but safe charging process should be adopted to enable workers on the block to safely exit the block in the event of an emergency.

The treatment of hot holes involves the use of various materials and procedures to reduce their temperature to below 40°C, after which the holes can be charged as normal holes. However, there was inadequate information available on chemicals such as cooling agents to make recommendations on their usage in reducing the temperature of hot holes. Available research revealed that cooling agents are used in dousing surface fires, but their effectiveness is reduced by their inability to access the source of the heat or fire (Eroglu, 2003; Phillips et al., 2011).The use of water as a cooling medium for hot holes is not recommended by mining and explosives stakeholders. In addition, Phillips et al. (2011) suggested that using water for cooling in hot holes above 80°C leads to steaming and/or the production of water gas. Water gas consists of two flammable gases, carbon dioxide and hydrogen, which are sources of ignition and a hazard to personnel working in that environment. Other ways of treating hot holes or managing their risk involve the use of foam expander plugs, gas bags, and PVC sleeves. Foam expander plugs (Figure 6) can be used to seal off venting holes, holes with temperatures that pose a high risk

Figure 6—Foam expander plug after sealing off a hole

to workers (holes with temperatures above the threshold), and breakthrough (or bhoboza) holes. Engagements with mining personnel revealed that, at high temperatures (approximately above 200°C), the solidified plug may catch heat and burn, releasing 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.

Gas bags can be used to seal off venting holes on a block. However, tests showed that sealing off hot holes with gas bags over long periods may cause them to burst or deflate, which would enable the escape of smoke from within the hole. It is recommended that, as part of a 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 are recommended for use as a form of physical separation between the surface of the hole and the hot-hole emulsion and as a container for the emulsion in breakthrough holes, cracked holes, and pillar holes. The sleeve works by retaining the water (approximately 17%–20%) inside the sleeve, which protects the explosive; only when this water has boiled off does the explosive rapidly increase in temperature until it reaches detonation temperature.

Conclusions and recommendations

A mixed methods approach consisting of qualitative and quantitative research was used to review SOPs and hot-hole temperature-measuring and -monitoring devices, to monitor and observe current hot-hole procedures at selected mines, to assess the effectiveness of various hot-hole management accessories, such as gas bags and PVC sleeves, and to collect and analyze temperature data. The results indicated that the management of hot holes requires a focus on pre-emptive risk assessment of mining blocks, the identification of hot holes using the correct temperature-measuring devices, and the continuous monitoring of hot holes from the time of drilling until just before blasting. Hot-hole management accessories, such as PVC sleeves, were found to be effective in insulating the hot-hole emulsion from the rock mass temperature, thus preventing the potential for premature detonation.

The following are recommended for incorporation into the SOPs for different mines to manage the risk of hot holes:

- *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 and calibrated. Information on what is being measured (the in-hole air temperature or the in-hole rock temperature) should also be clearly specified.

It is further recommended that mines should consider the following in the selection and use of temperature-measurement and -monitoring devices:

- Mines to advise manufacturers to consider further technological design changes on both temperature-measurement and -monitoring devices to ensure that they 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 better separate understandings of the rock and air temperatures. 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.

- When the heat source is near the top of a hole, it is far more dangerous than when the heat source is at the bottom of a hole because heat rises and there is less explosive to heat at the top of a hole before it gets to critical temperature.
- Temperature-monitoring devices selected should be audible in the presence of explosives trucks during charging and have multiple measuring points along the explosive column.

Regarding the charging and blasting of hot holes, it is recommended that mines select explosives products and accessories for use in hot-hole environments based on the mine site conditions and the associated risk assessments. Furthermore, it is encouraged that large-scale tests on the explosive products should be conducted at the mining sites to enable identification of the full spectrum of risks associated with blasting in such environments.

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