MANAGEMENT OF REACTIVE GROUND AT THE GOEDGEVONDEN OPENCAST COAL MINE IN THE WITBANK COALFIELDS OF SOUTH AFRICA

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Gabriël LeRoux Botha, ID 750102 5075 086)

7th day of October, 2014

This research report is dedicated to my late father, Gabriël LeRoux Botha, whom passed away during the time of my study (29 April 1945 to 29 January 2013).

ABSTRACT

Reactive ground has been identified as the primary cause of a blasting incident at Goedgevonden Colliery in South Africa late in 2010. Current practices as well as potential new mitigating opportunities were investigated to ascertain what steps can be taken to reduce the risk of a repeat blasting incident due to reactive ground.

To effectively manage the risk of reactive ground; current practices and potential new opportunities were investigated. A literature study of reactive ground highlights the major differences between spontaneous combustion and reactive ground, directing the study towards specific tools that will assist in the management of reactive ground.

The research includes finding with regards to:

- Reports and recommendations from mining personnel, a 3rd party laboratory and explosive suppliers,
- Stemming methods,
- The use of Liners in blast holes,
- Incorporating Thermal imaging cameras in the process of identifying elevated temperatures,
- Investigating the Pieter van Jaarsveld method for ‘on the block’ testing for reactive ground,
- Investigating the allowable temperatures of explosives and the temperatures in the hole, highlighting the importance of blasting the holes immediately when explosive temperatures exceed 90°C,
- Temperature monitoring equipment available in the immediate market.

As a conclusion to the study recommendations are made that will assist the mining house to produce a procedure that will reduce the risk of working in reactive ground.

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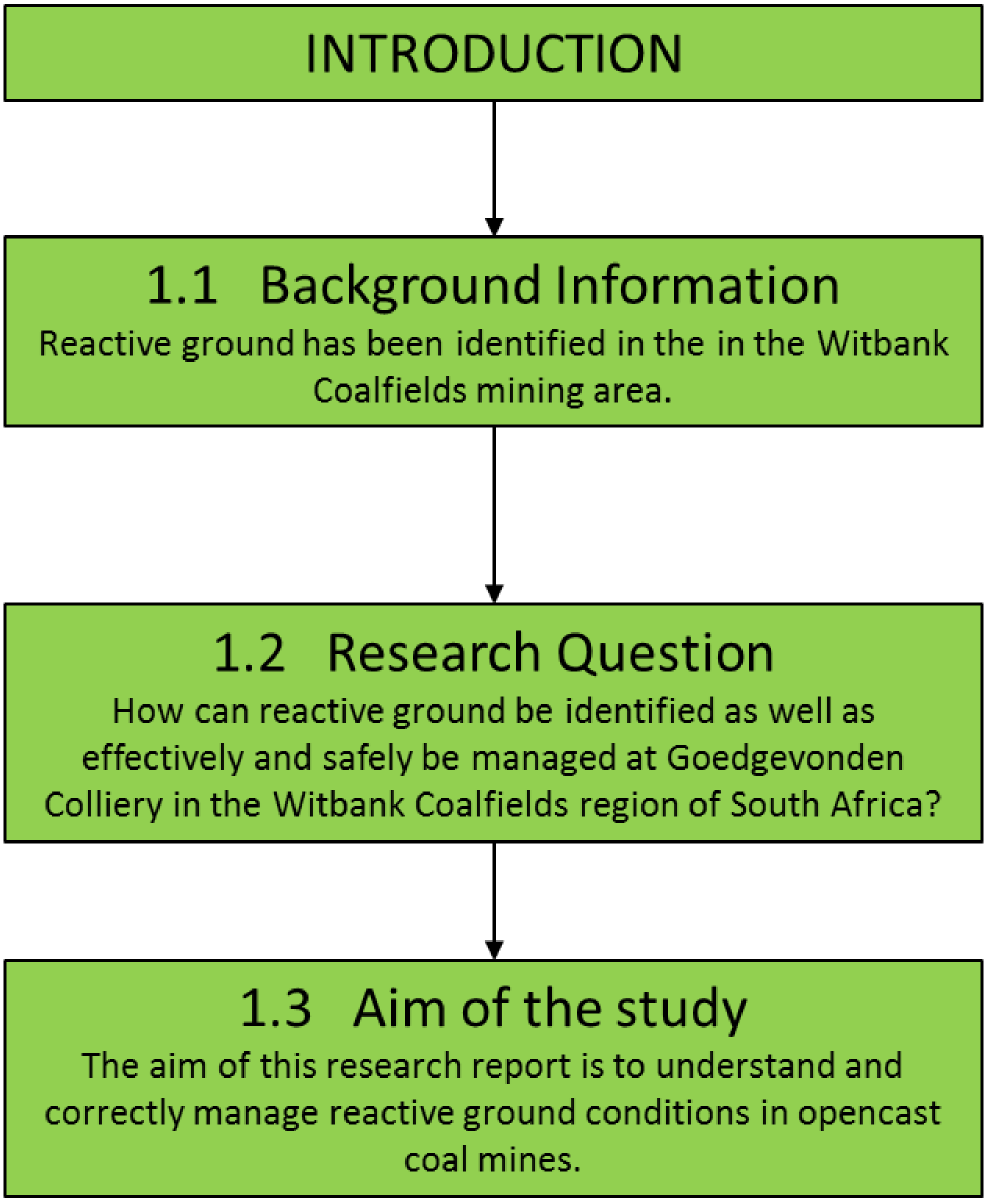


INTRODUCTION

1.1 Background Information

Reactive ground has been identified in the in the Witbank Coalfields mining area.

1.2 Research Question

How can reactive ground be identified as well as effectively and safely be managed at Goedgevonden Colliery in the Witbank Coalfields region of South Africa?

1.3 Aim of the study

The aim of this research report is to understand and correctly manage reactive ground conditions in opencast coal mines.

1. INTRODUCTION

1.1. Background Information

Reactive ground has been identified at Goedgevonden Colliery in the Witbank Coalfields mining area. Reactive ground is a term used to describe ground in which a large amount of reactive sulphides is found, especially iron and copper sulphides. This ground is prone to react with the bulk explosives used in fracturing the rock, normally associated with mining activities, and can lead to a quick and unstable rise in temperature in the blasthole before controlled ignition of the blasthole can take place. The main ingredient in bulk explosives used on surface coal mines is ammonium nitrate. This type or reaction is more common, especially in iron and copper mines, but some incidents have been recorded in opencast coal mines.

An incident occurred at Glencore Goedgevonden Colliery, directly related to reactive ground. On the 21st of October 2010, the blasting crew at Goedgevonden Colliery was busy charging and preparing for a blast on a block of waste above the number 4 coal seam. The charged block was left overnight on the 20th, to be completed and fired the next day. At approximately 14:30 on the 21st, while tying up the charged block for firing, five holes initiated prematurely while the Blaster and two assistants were still on the blast block. No one was injured in the event. Smouldering and smoke only became evident on the blast on the days following the incident.

Sasol Nitro Opencast Operations were called in to assist with the investigation. Tests were done to determine the oxidative sulphide reactivity of the shale when in the presence of ammonium nitrate. Ammonium nitrate can react with sulphide containing minerals in an auto-catalysed process as it generates its own catalyst as it proceeds. This means that after some induction time, runaway exothermic decomposition can take place as shown by Rasnik (2000). This reaction can occur even when the ambient temperature is as low as 20°C. The tests showed that high iron and sulphide levels were present in the shale and the reactivity of the shale was confirmed in the study of Delagey (2010).

Previous recorded incidents, as stated in the Briefing note on reactive ground, version 6, by Orica mining services, 2013, were noted as follows:

- “Mt. Leyshon in 1992, detonation of a shot hole where Emulsion explosive were left in the hole for several months;
- Collinsville Coal in 1995, shot holes that contained a ‘TES Emulsion’ (HEF) explosives, caught fire;
- Collinsville Coal in 1998, a shot hole loaded with Sawdust/ANFO detonated prematurely;
- Sons of Gwalia in 1998, several holes at the Jacoletti pit started smoking within 20 minutes of being loaded with heavy ANFO;
- Century Zinc in 1998, ammonium nitrate spilled on the bench started to burn several days after the shot was fired.”

Numerous studies have been undertaken in the Witbank Coalfields area regarding spontaneous combustion and hot-hole blasting. The standard operating procedure states that observations should be done for hot-holes. Blasts should be treated accordingly when these conditions are found.

Spontaneous combustion is a major hazard when mining and handling coal in Southern African coal mining operations. It occurs by means of an oxidation reaction without an external heat source, changing the internal heat profile of the material, and eventually leading to a rise in temperature (Phillips, Uludag, & Chabedi, 2011). This can then eventually lead to an open flame and burning of the material. It is a natural phenomenon occurring in and around coal seams and gets aggravated when exposed to mining activities.

The development of the Goedgevonden Southern Pit is completely in a virgin coal field where no previous underground workings previously took place. It was therefore assumed that the holes would not be heating up dramatically due to spontaneous combustion as usually found when working above old underground workings. Thus, no heat monitoring equipment was used during the blasting preparations.

With no formal management structure in place for the operation to deal with reactive ground and its effects on blasting at the mine, a study was suggested to determine what steps could be taken to ensure the identification of, and safe working conditions when encountering reactive ground in the operations.

1.2. Research Question

How can reactive ground be identified, as well as be effectively and safely managed at Goedgevonden Colliery in the Witbank Coalfields region of South Africa?

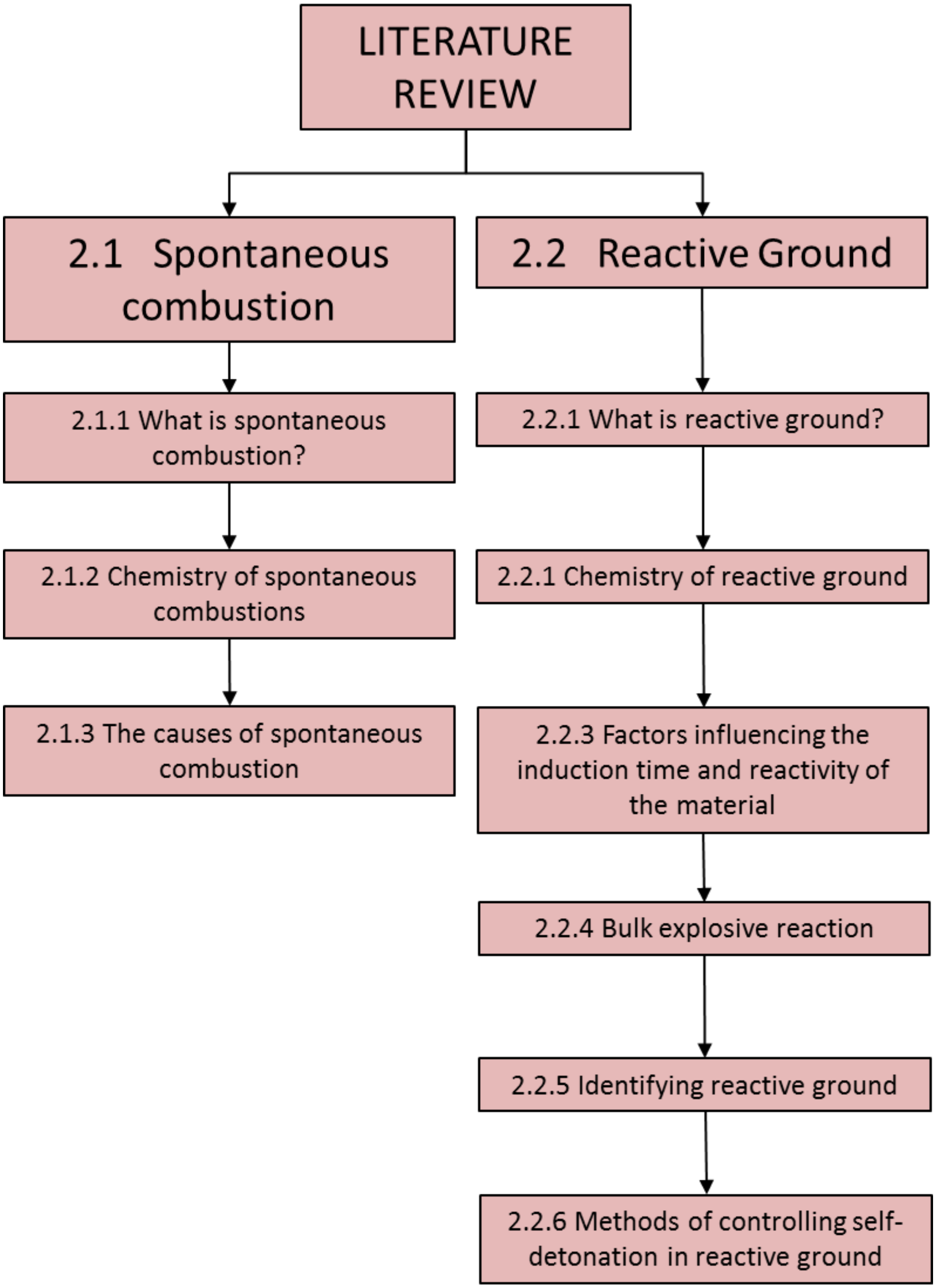
1.3. Aim of the Study

The aim of this research report is to understand and correctly manage reactive ground conditions in opencast coal mines. This will include the means to identify potential reactive ground areas, as well as formalising methodologies to manage these areas when encountered in the mining environment.

With regards to the identification of potential reactive ground areas, the study will focus on basic geology and components that may lead to a reaction that will increase the temperature of the host rock. Visual identification, specialised equipment, and conclusions drawn from geological models will be identified that could help isolate and treat the areas in order to mine safely throughout the affected areas.

With regards to the management of reactive ground, mining strategies and action plans must be investigated to quickly and effectively deal with the reactive ground areas when suspected or encountered. This study will attempt to generate effective options that could be followed in order to develop an efficient management plan that will assist in minimising the risk of working in reactive ground conditions.

CHAPTER 2 - LITERATURE REVIEW



2. LITERATURE REVIEW

The literature review will describe the key concepts of the research report by explaining the heating of coal in its natural state by means of spontaneous combustion as well as describing the process of reactive ground.

To understand the term reactive ground, confusion must be removed with regards to the spontaneous combustion of coal. The differences between spontaneous combustion and reactive ground will be explained in this chapter. This will assist in formulating the correct action plan when either of the processes is encountered in the operations.

2.1. Spontaneous Combustion

The information contained in the following sections has been taken from the Coaltech Research Association's *Best Practise Guidelines for Surface Coal Mines in South Africa - Prevention and control of spontaneous combustion* compiled by Phillips *et al*. (2011).

2.1.1. What is spontaneous combustion?

When oxidation of coal occurs without an external heat source, it is termed as spontaneous combustion. It is a process whereby changes of the internal heat profile of a material lead to a rise in temperature of that material. The temperature can increase to a point where ultimately open flames and burning of the material can occur.

2.1.2. Chemistry of spontaneous combustions

When coal is exposed to oxygen the process of oxidation occurs. This process produces heat. If the heat is allowed to dissipate the surrounding temperature will not increase. However, if the heat remains contained, the temperature will increase and the oxidation process will increase exponentially until ignition of the material occurs.

The following intrinsic factors play a role when coal is found to be sensitive to self-heating:

- The coal composition, quality and texture;
- Coal friability, its particle size and exposed surface area;
- The inherent moisture of the coal; and
- The amount of Pyrites found inside the coal.

The increase or decrease of heat in coal will depend on the following external influential factors:

- Thermal conductivity of the coal as well as the surrounding rock.
- Convection processes caused by the exposure to wind.
- Barometric changes in the atmosphere.
- Local climate.
- The presence of organic material in and around the coal seam.
- The density of minor and major fractures throughout the rock mass.
- The most important external factor that is probably related to the self-heating of coal is the mining method. The method used in exposing and extracting coal influences the amount of exposure the coal will have to the previously mentioned external factors. The mining method also influences the time for coal to be exposed to oxidation.

When looking at spontaneous combustion at a production site the following factors can also increase exposure to oxidation:

- Stockpile management of coal with regards to the method of stockpiling, the compaction, as well as the height of the stockpile.
- Stockpile management of waste dumps with regards to the method of stockpiling, the compaction, as well as the height of the stockpile.
- The maintenance of exposed coal faces in open excavations.
- In underground mines the strata formation, mining method and ventilations of the current and old working will play a big role in exposure to oxidation.

In describing the heating process of combustible matter, Arrhenius' law (Querol Aragón, García Torrent & Cámara Rascon, *s.a.,* as cited **in** Phillips, *et al.*, 2011) is used to calculate the reaction:

At normal ambient temperatures combustible matter can react with oxygen and release heat. When the conditions allow, the spontaneous heating will increase the reaction rate and, hence, also increase the heating process. Initially the heating process can be undetected and very minor, but if the oxidation process is allowed to continue, the temperature will gradually increase and the reaction rate will increase exponentially.

Arrhenius' law

$$V=C_r\ .\ C_oA.e^{(Ea/RT)}$$

V = reaction (mol g $^{-1}$ s $^{-1}$)
C_r = combustable concentration (kg/m^3)
C_o = Oxygen concentration
A = Arrhenius' Frequency Factor (s^{-1} or $s^{-1}C^{1-n}$)
Ea = Activation Energy (KJ/mole)
R = Universal gas constant (8.314 J mole K^{-1})
T = Temperature (K)

2.1.3. The causes of spontaneous combustion

Some of the more common causes of spontaneous combustion can be found in the following instances as outlined in the Spontaneous Combustion Guidelines compiled by the Coaltech Research Association.

Underground mining operations

Crushed coal or fractured pillars can oxidise when exposed to slow airflow in old underground workings. Too little airflow will not allow oxidation, and on the other hand, good ventilation will keep the workings cool and heat will not be able to build up.

Surface mining operations

Oxidation can take place in surface stockpiles of coal, or waste containing coal, if the stockpiles are not properly compacted and airflow is allowed to penetrate the heaps.

Even compacted stockpiles can eventually be exposed to oxidation with rain causing erosion and creating airflow throughout the stockpiles. Heat then builds up in these stockpiles and remains trapped in the stockpiles, therefore aggravating the self-heating of the coal.

Spontaneous combustion also takes place in the spoil heaps of surface strip mines, where high ash carbonaceous shale surrounding the coal is vulnerable to heating. This is especially true when dragline stripping of the waste is done. The dragline spoils are un-compacted, and can contain coal and shale as the dragline exposes the coal seam. The spoils are generally high and exposed to the natural elements. Some coal mines suffer from severe fires in the spoils piles due to spontaneous combustion of this shale and coal.

2.2. Reactive ground

Generally all coal can be vulnerable to spontaneous combustion when exposed to oxidation and self-heating can take place over time. Reactive ground, however, does not affect coal in general and is observed only within coal and shale that displays certain characteristics.

2.2.1. What is reactive ground?

Reactive ground can be defined as ground that contains high concentrations of sulphides that have the potential to self-heat and will have a reaction with Ammonium Nitrate explosives(Han, Freij, Feng, Gunawan, Zhang, & Waters, 2005). When these sulphides react with Ammonium Nitrate bulk explosives in and around a blasthole, the reaction can result in a quick and unstable rise in temperature that will eventually lead to uncontrolled deflagration or detonation of a blasthole.

2.2.2. Chemistry of reactive ground

According to a paper done by Kennedy and Tyson (2001), and the AEISG *Code of Practice for Elevated Temperature and Reactive Ground* (2007), there are several stages through which the reaction evolves until it eventually ignites. These stages are described below and are also illustrated in **Figure 1.**

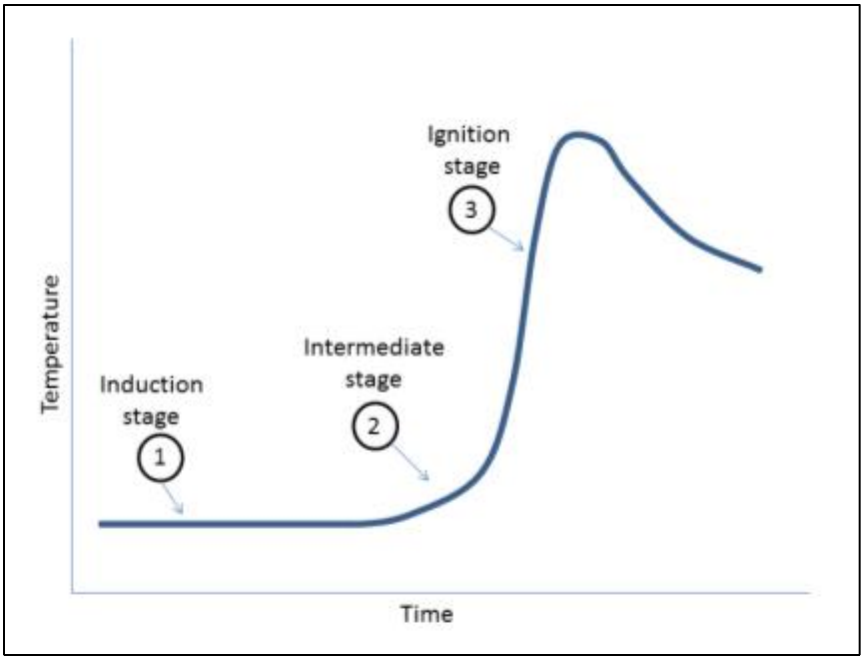


Figure 1: Typical Time vs. Temperature profile for an ammonium nitrate / sulphide reaction (taken from Kennedy and Tyson, 2001)

When iron sulphides, such as pyrites are exposed to atmospheric oxygen, natural oxidative weathering can take place. This stage of the reaction is called the ***Induction stage*** and could occur over days or even weeks. This can happen along exposed surfaces such as the mining pit walls, cracks throughout the material, drilled production holes and especially once the area is fractured after blasting. This then generates a solution of ferrous iron and acid. No nitrates are necessary for this reaction to take place. This is an exothermic reaction and the temperature of the ore can increase by as little as 2°C to several hundred degrees, depending on the reactivity of the ore.

Iron sulphides + oxygen + water → ferrous ions + sulphuric acid
(Kennedy and Tyson, 2001)

During the ***Induction stage***, ammonium nitrate is present and a chain reaction begins, the ferrous ions and sulphuric acid will begin the autocatalytic process of breaking down the nitrate.

Ammonium nitrate + iron sulphides + ferrous ions + sulphuric acid → nitric oxide + ferric ions + heat
(Kennedy and Tyson, 2001)

The nitric oxide and ferric ions generated from this reaction then also react with the pyrites, and this in turn generates even more ferrous ions and sulphuric acid.

Iron sulphides + nitric oxide + ferric ions → ferrous ions + sulphuric acid
(Kennedy and Tyson, 2001)

Even though this reaction is exothermic, the reaction rate may be slow due to the concentration of the catalytic types needed to build up to a critical level. This could make it difficult to initially detect any significant rise in temperature.

Once the induction period (the initial slow stage of the chemical reaction) has passed, a sharp increase in temperature can be observed as the rate of the reaction increases. This is called the ***Intermediate stage.*** At this stage of the reaction the temperature can increase by more than a 100^{o}C in only a few minutes. You may be able to see reddish-brown fumes (nitrogen dioxide) just before the reaction moves over to the next stage.

The ***Ignition stage*** of the reaction can be very fast. If there is sufficient fuel and the physical parameters are met with regards to the confinement and critical diameter of the blast hole, violent decomposition of the remaining ammonium nitrate in the solution can and will occur. This detonation can occur even when a detonator or booster hasn't been placed in the blast hole. If these physical parameters aren't ideal for detonation, it can still result in deflagration and pyrite fires.

Ammonium nitrate + heat → explosion

(Kennedy and Tyson, 2001)

2.2.3. Factors influencing the induction time and reactivity of the material

Kennedy and Tyson (2001) identified some factors that will have an impact on the reactivity between reactive ground and ammonium nitrate and the time of the chemical reaction. These factors include moisture content, acid content, mineralogy, thermal properties, ambient temperature of the host rock, temperature of the bulk explosive, as well as the particle size of the material. The factors are described below.

Moisture content: Kennedy and Tyson (2001) stated that the moisture content of the host rock or material will have a role in the reaction, as water is a natural catalyst for oxidation. The study of Rumball (1991) explained that too little water will only restart the aqueous phase of the reaction process. Too much water will assist in diluting the reactants and will consume the heat of the reaction through endothermic dissolution of the ammonium nitrate. The ideal amount of water that will influence the oxidation process is dependent on the rock type but range typically from 2 - 5%.

Acid content: Field studies have not been able to draw a direct correlation between in-situ pH of the host rock and reactivity. But the more acidic the environment the faster the reaction rate in the induction stage will be (Kennedy and Tyson, 2001).

Mineralogy: An increase in ferrous ions will lead to an accelerated reaction rate. Sulphide minerals can generate heat through spontaneous combustion. This in turn accelerates the rate of the reactivity reactions. Partial oxidation of sulphides can lead to a potential increase in reactivity because it creates an acidic environment as well as ferrous ions needed to intensify the reaction (Rumball, 1991).

Thermal properties: Sulphides, shale, coal and ammonium nitrate have low heat conductivity properties. This means that they cannot conduct heat away from the source. Because of this property, it may require only a small heat input to generate significant increases in temperature, and this in turn will increase the rate of the reaction (Rumball, 1991).

Ambient temperature: There is a correlation between the ambient temperatures of the drilled hole with the rate of the reaction. A higher temperature will increase the rate of the reaction (Kennedy and Tyson, 2001).

Temperature of the bulk explosive: After the bulk explosives is sensitised and pumped into the blasthole, the product can possibly have a higher temperature than the surrounding ambient temperature due to the gassing process. This may also have an effect on the reaction rate of the reactive ground and the ammonium nitrate (Kennedy and Tyson, 2001).

Particle size texture: As more surface area becomes available for the reaction, the rate of the reaction will increase (Rumball, 1991). The particle size, its distribution, reaction mass, as well as the confinement of the host rock greatly influences the reaction with ammonium nitrate as it creates a larger transport mass, therefore increasing the accumulation of heat in the reaction. Lukaszewski (1968) noted that the ignition temperature of a sulphide bearing ore will decrease as the particle size of the material decreases. This is an indication of increased reactivity in finer particle size material.

It was also noted that a definite ignition temperature can only be achieved if the particle size of the ore is homogeneous. Therefore, a perfect temperature cannot be indicated for the threshold of spontaneous combustion, but rather a range of temperatures from around 300°C upwards.

Increased compaction and confinement of the material will also lead to a slower rate of oxidation. The most reactive particle size would therefore be fine dust, followed by broken ore, as would be found after a blast of the rock.

An in-situ drilled block would then follow the reactivity of broken ore due to the amount of surface area available for reaction, as the drilled holes give an increased reaction surface throughout the blast block. For example, a 100m in length by 65m width blast block, would expose 6 500m^2 surface area. A 5m burden by 5m spacing pattern is then drilled with a 251mm diameter drill to a depth of 6m. Each hole will increase the exposed surface area by 0.95m^2, in total increasing the surface area to 6 746m^2, an increase of 4% surface area.

The least reactive material would be unbroken in-situ material without the presence of fine reactive dust on the surface.

2.2.4. Bulk Explosive reaction

In order to better understand the reactivity process, the reaction temperatures of bulk explosives typically used in opencast coal mines is studied. The bulk explosives used in opencast coal mines are usually made up from oxidisers and fuel. A small percentage of the explosive is made up of other inert materials. The explosive reaction was studied by Rorke (2004) and can be described as follows:

The oxidiser supplies oxygen that can combine with carbon from the fuel and this forms carbon-dioxide gas (CO_2). There is also a reaction between the oxygen and the hydrogen that is present in the fuel. This reaction forms water vapour (H_2O) as well as nitrogen gas.

Ammonium nitrate + fuel → gas + water vapour

The Blasting Technology Department of Bulk Mining Explosives (BME), a member of the Omnia Group, conducted studies on the reaction temperature of their two main products available for use in the opencast mining industry (Rorke, 2004). A pure emulsion explosive, HEF100 (a 100% emulsion composition), an ammonium nitrate emulsion mixture, HEF207 (containing 30% ammonium nitrate prills), and HEF206 (containing 40% ammonium nitrate prills) were tested. These are the most common types of explosives used in the Witbank Coalfields area. Because of its good water resistant properties it can be left in water filled holes without breaking up for weeks (BME, 2008).

Samples of sensitised explosives were heated by exposure to an intense heat source (in this case a blow torch), and the temperature increases were recorded. The results were documented using video recordings and a seismograph. Each of the tests recorded an event where the explosive erupted from the collar of the test pipe and temperature readings were recorded for an additional 10 minutes after the event. The samples reacted similarly during the testing and the following conclusions were drawn from the data gathered:

- The samples did not produce a violent detonation, but at 320°C a heat generating reaction did occur in each case.
- A boiling point of the emulsion was recorded in the region of 150°C. If the source temperature rises above this temperature in a borehole the product will boil and dry out and in due course lead to a reaction. This reaction produces low amplitude, long duration pressure waves with measured temperatures of 500°C in the charge. It is concluded from the tests that if similar conditions occurred in the blasthole, it will result in the ejection of the remaining explosives from the blasthole. The temperatures and pressures generated are not enough to detonate the entire blasthole.

It can therefore be concluded that the risk of detonation of the bulk explosive in a blasthole due to an increase in temperature does not present itself below 320°C. Investigations should be focussed on the protection from heat for detonators and boosters in blastholes because they are known to be sensitive to heat from as low as 80°C. If the detonator detonates, the risk of the entire explosives column detonating increases dramatically. It is imperative that the lowest temperature component of the blasthole be used when creating a risk management programme where a temperature limit is set to mitigate the dangers when working in an increased temperature environment, (Rorke, 2004).

2.2.5. Identifying reactive ground

There is no definitive means to identify reactive ground or the reactivity of the sulphides in a rock. There are however some tests available to assist in identifying potential reactive ground. It is very important to note that the reactive bearing mineral in the rock is not the only determining factor that influences the risk in working around reactive material. As stated previously, some factors influence the rate of the reaction. The sample reactivity should therefore not be viewed in isolation. Kennedy and Tyson (2001) described some of the sampling and testing techniques as follows:

2.2.5.1. Geological and field tests

Geological field investigations should be the first steps taken to research reactivity of the ground. The reliability of the results is highly dependent on the level of confidence at which the geological survey has been done. If the geological confidence is low, the mine would have to resort to a more conservative approach when advancing to potential reactive ground areas. This action can increase the cost involved due to the larger unknown factor involved that will influence the exposed risk. Additional safety measures would then have to be taken over a larger suspect area.

When sampling for reactive ground, the sample should be kept as pure as possible, and kept as clean as possible from outside contaminants, or diluted from surrounding rock. This will lead to a test result giving the most accurate indication of the reactivity of the rock. Diamond drill core sampling will be most ideal for these tests, allowing clear boundaries in the specimen and less dilution from non-reactive material in the sample. Hand specimen sampling directly from the test area should also yield a relatively pure sample.

Drill chippings from the test area can also be used, and it is believed that it may be advantageous due to the fact that the material may already have been exposed to some oxidation. However, the sample should be stored in such a way as to prevent further oxidation from the time of the sampling to testing. It is also important to try and test the drill chippings material, after it has been exposed to oxidation around the same time that it would normally take between drilling and charging of the blast block. The negative aspect of drill chipping sampling is that the sample may be severely diluted from non-reactive material. The reactive part of the material may only be a smaller percentage of the hole and therefore misrepresent the potential danger in the sampled area (Kennedy and Tyson, 2001).

2.2.5.2. Laboratory testing:

Small sample test (20mg-1g)

Differential Thermal Analysis (DTA) and Thermo-Gravimetric Analysis (TGA)

DTA and TGA are well established analytical techniques used to investigate the thermochemical properties and the reactivity of a material. In the case of Lukaszewski (1968), a Du Pont Thermo-analyser was used to make comparisons of the thermal stability of various sulphides and ores as it expresses both DTA and TGA.

DTA and TGA tests are done using a small sample from around 20mg to 1g. The temperatures measured in the tests may not be completely indicative of the actual temperatures that may occur in the field due to the fact that only a small sample is used in the testing. The results are only used to rank reactivity.

DTA tests produce a differential temperature trace between heat source and the temperature of the sample. Observed spikes in the trace will be an indication of an exothermic reaction taking place. The temperature observed directly before the spike will be identified as the onset temperature. This is the main indicator of reactivity in a material.

TGA tests can run concurrently with DTA tests and involve the weighing of the sample as it gets heated. A weight loss curve gets generated throughout the testing. The curve will indicate the expulsion of gases from the sample as the reaction occurs (Kennedy and Tyson, 2001).

Medium sample test (20g-50g)

Dewar test

The Dewar test is very similar to the DTA test, however done at a much larger scale. Because of a better ratio between surface and volume, the gaseous reaction products are retained in the sample for a longer period and therefore results in a more indicative result as to what could occur in the field. Firstly, a 20g-50g sample would be ground to less than 250μm. The powdered sample is then mixed with an emulsion matrix. A catalyst may be added to the solution. The reactants are then placed in a Dewar flask. The Dewar flask is then placed in an oven heated to a specified temperature, for example 50^{o}C or 70^{o}C. The oven is then either held at that temperature until some reaction is observed or the oven will be cooled down to the normal ambient temperature.

Large sample test (1kg-2kg)

Large scale testing can be considered to bear the most realistic results. This test will represent the actual scenario that may occur in the field. It requires oven tests that use a realistic charge diameter and test duration similar to what can be expected in the field. The test requires 1kg to 2kg inhibited emulsion matrix / Ammonium nitrate prills, mixed with powdered ore and a catalyst into a large tin can (150mm diameter). The oven, as per the Dewar test, is heated to a specified temperature for a period of hours until the core temperature is stabilised, the temperature is kept constant and the sample monitored (Kennedy and Tyson, 2001).

2.2.6. Methods of controlling self-detonation in reactive ground

The following control methods were discussed by Kennedy and Tyson (2001) and are reviewed to indicate some possible protocols that may be available for the management of reactive ground. This can be explored further to understand key concepts that can be adopted and assist in generating a conceptual model that may help to decrease the risk associated with reactive ground mining.

2.2.6.1. Temperature logging:

The first and foremost test to be carried out to ensure that the hole is safe for charging is to monitor the temperature in the hole to be charged. The logging of temperature is usually done in conjunction with other control methods as it is only an information system allowing the implementation of other controlling measures. Kennedy and Tyson (2001) have identified two instruments that can log the temperature of drilled blast-holes. Thermocouples can be used to measure the temperature of the air in the hole or of the hole sidewall itself if contact can be established and maintained between the probe and the sidewall. There are also a number of Infra-red logging devices available on the market that only needs to be directed at the target and can easily and very quickly measure temperature readings of blast-holes.

African Explosives Limited (AEL) Mining Services has been developing some specialised equipment that may assist in detecting hot holes on surface coal mines and therefore reducing the safety risk when working in these areas. They recently launched a blasting accessory product, the “Blast Eye” hot hole monitor. (AEL Mining Services. (2013).This temperature monitoring device delivers an intermittent alarm when it reaches 60^{o}C, and the alarm will become continuous when the temperature in the hole increases to above 80^{o}C. This is then the indication that the hole is not safe under normal blasting procedures and that the personnel should evacuate the block and start procedures for dealing with the risk (AEL Mining Services. (2013).

The “Blast eye” is made up of a hand held device with a temperature probe attached to a 30m wire. The probe is placed in the hole to be monitored and destroyed with the blast. The product is made of disposable materials and is relatively affordable (AEL Mining Services. (2013).

2.2.6.2. Load and shoot:

This method is usually used when the mine has recently discovered the presence of reactive ground and is the first step in minimising the risk of premature detonation or deflagration of a shot hole. A maximum time period can be implemented to complete the charging and blasting of an area where reactive ground is identified or suspected. The number of hours allowed for the completion of the charging and blasting is dependent on the knowledge available regarding the reactivity of the material in the area (Kennedy and Tyson, 2001).

2.2.6.3. Specialised stemming material:

The stemming of a blast-hole can be a critical factor when dealing with reactive ground. Both stemmed and un-stemmed holes have been recorded to self-detonate and deflagrate. Stemming may prove to be a greater risk in reactive ground as the material can consist of drill chipping that also may contain reactive material. As discussed previously under the factors that may influence reactivity, the greater surface area exposed to reaction may greatly increase the rate of the reaction in the hole. Un-stemmed holes on the other hand may be more prone to only deflagrate. Warning of heating in the hole may be visible when the gaseous product of the reaction escapes the hole. Therefore, it is essential to assess whether the holes in a reactive ground area should be stemmed at all, and in the cases where stemming is definitely required, that an inert stemming material should be imported to site. Sand or gravel can be used to stem the holes when needed (Kennedy and Tyson, 2001).

2.2.6.4. Physical separation:

Kennedy and Tyson described physical separation techniques as per the research conducted by Bellairs, Hellyer, Scales, Travers & French (1999) as cited **in** Kennedy and Tyson (2001). By reducing the contact between the reactive sulphides and the ammonium nitrate based explosives, reaction can be retarded. Borehole liners and packaged explosives are readily available products that can assist in the physical separation of the reactants. When using borehole liners it may be possible to completely separate bulk explosive from the surrounding material. The explosive is pumped directly into the liners and lowered into the hole where no contact is made between the explosive and the sidewall of the hole.

When using liners in blast holes it may be possible to use conventional uninhibited bulk explosives because no contact is made between the explosives and the host rock. The risk, however, with liners is that it is only effective as long as the liner stay completely intact and no tears or rips are formed in the liner when pumped with explosives or lowered into the hole. The risk may be too high to allow the use of uninhibited bulk explosives with liners in a highly reactive environment.

The liners may also be difficult to charge up with explosives. Spillages on surface can occur on the sides of the liner or on surfaces surrounding the hole, where it may come into contact with reactive drill chippings. The cost of the liners and additional labour costs in order to manage and handle the liners can also be noted as disadvantages when considering using liners to prepare blast blocks in reactive ground.

Packaged explosives are similar to normal bulk explosives in their composition. The difference is that the explosive is wrapped in tight rigid plastic packages that can be lowered into the blast-holes without any contact with the surrounding material. These wrappers are usually more resistant to tearing than liners and can be used effectively in smaller diameter holes.

2.2.6.5. Inhibited explosives:

Some investigations have been made to determine what inhibitors can be added to ammonium nitrate in order to inhibit or slow down the reaction between reactive sulphides and ammonium nitrate. The United States Bureau of Mines have conducted studies regarding these inhibitors and concluded that urea (NH_2CONH_2) is the preferred component to inhibit the reaction as it helps to trap the catalyst and prevent reaction (Kennedy and Tyson, 2001).

Recent advances in technology have led to economical ways to incorporate these inhibitors in the bulk formulation, thus inhibiting the reaction of ammonium nitrate prills with reactive sulphides. It is still very important to note that various products on the market may not all have the same impeding effect and each product should be analysed to formulate a safe working time in which the product can be left in the hole before the reaction escalate and becomes a risk (Kennedy and Tyson, 2001).

In the case of the paper, *Inhibited Explosive versus liners to safely blast a reactive rock type at the Mt Whaleback iron ore mine*, by Bellairs, Hellyer, Scales, Travers & French, (1999), blast hole liners were completely substituted by using an inhibited bulk explosive. The reasons were stated as follows:

- Overall blasting costs were reduced due to the removal of the liners.
- Exposure of uninhibited explosive to the reactive atmosphere due to tears or rips in the liners is eliminated.
- The charging time is reduced because the blasting crew do not have to waste additional time in cleaning spilled explosives from the sides of the liners.
- The risk of spilled uninhibited explosives heating up and reacting with the initiating systems on the blast block is removed.
- Liners can tear in case of a misfire, and this may expose uninhibited explosives to the surrounding reactive ground.

2.2.6.6. Integrated risk management:

The integrated risk management approach is an effective tool that can assist in managing and reducing the risk of reactive ground in opencast operations. This approach will ensure that documentation is put in place and auditable to make sure that all major hazards regarding reactive ground are correctly recognised in the field through the management plan, thoroughly assessed and effectively controlled. This will lower the risk of working in reactive ground to as low as practically possible. This approach will also allow the mine to design practical solutions that will fit in optimally on site for its specific circumstances.

Kennedy and Tyson (2001) developed an integrated risk management program where they placed emphasis on engineering safe and cost-effective controls that will manage the risk of reactive ground and prevent the workers from being exposed to unacceptable levels of risk. They presented procedures as detailed below:

People involved in the management process should include senior management, explosive supplier representation, the Technical Services Engineer, production supervisors, regulatory authority personnel, and the relevant site geologists, as they are all affected by decisions throughout the management process and their inputs will be critical in mitigating any hazards. As seen in **Figure 2**, a management process was mapped and the framework detailed to ensure compliance and understanding of the requirements and controls in the management process.

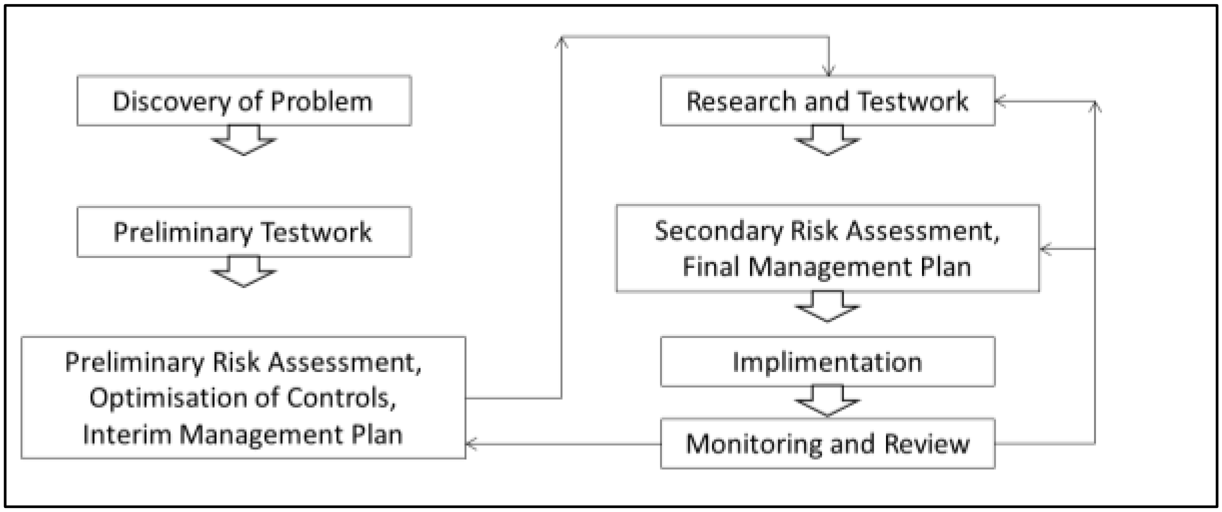


Figure 2: Schematic representation of the Kennedy and Tyson (2001) Management process

This process allows for basic steps to follow that will assist in controlling the management of reactive ground when encountered on a mining site. The following points elaborate on the process and explain the steps required to manage the risk.

Discovery of the problem and the preliminary test work

Once it is suspected or an incident occurred that indicated the presence of reactive ground on a site, all stakeholders need to be notified and necessary testing need to be done to evaluate the level of the hazard the mining operations will be exposed to. The explosive suppliers will present their analysis and recommendations regarding the reactivity testing.

Preliminary risk assessment

A preliminary risk assessment should be done based on the location and severity of the reactive ground problem. The “Reactive ground fault tree” and a “Semi quantitative risk assessment” will be used for the assessments.

Optimisation of controls and the interim management plan

The proposed procedures and processes will need to be reviewed and optimised by the stakeholders with regards to cost and efficiencies as some of the controls may be effective, but cheaper or easier implementable solutions may be available.

Research and test work

An action plan will be signed off by all the stakeholders putting detailed test work in place to increase the effectiveness of the instituted controls and investigate further measures that may improve the proposed solutions and controls.

Secondary risk assessment and the finalised management plan

A second risk assessment must be completed. A review of the research and testing will be done and possible oversights in the initial risk assessment identified and controls updated. Procedures should include all the loading and blasting processes, including the management of misfires in reactive ground. The stakeholders will sign off the management plan that must provide procedures that reduce the level of risk to conform to industry best practice.

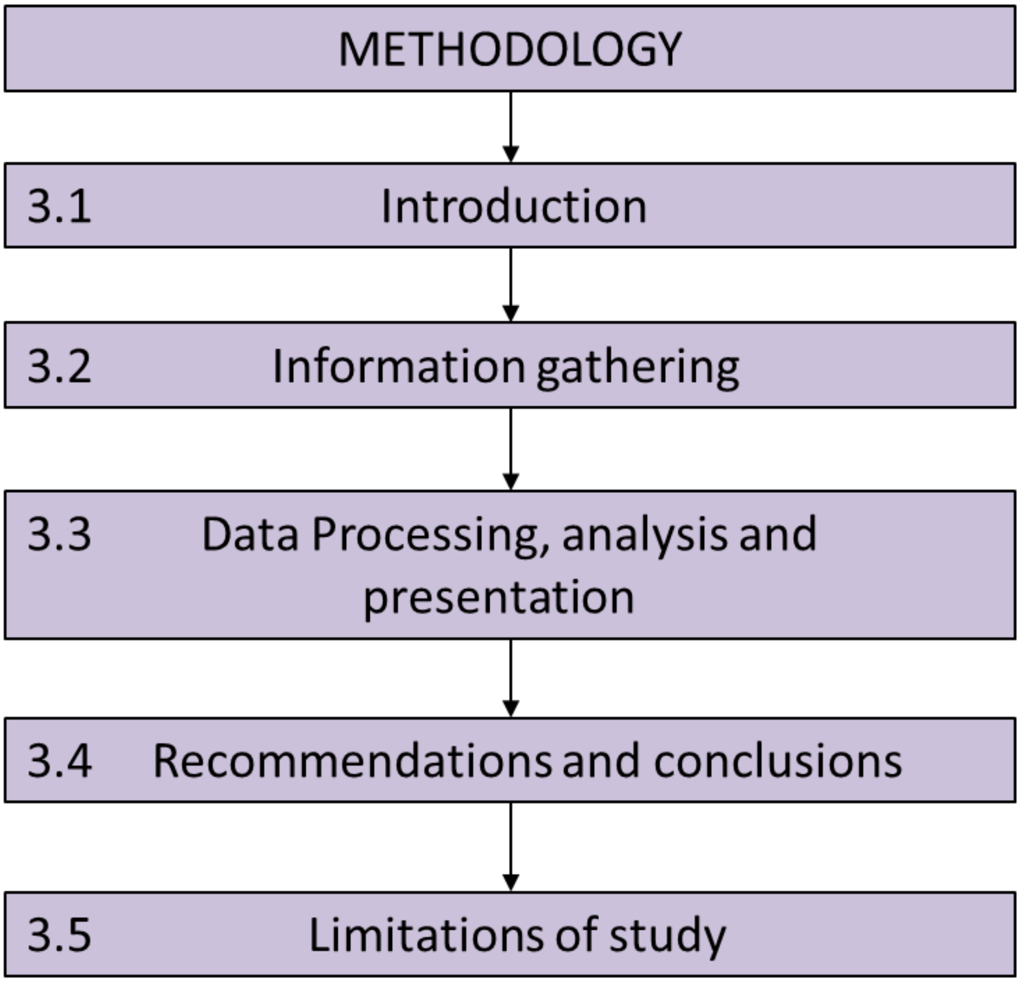
Implementation

Implementation must be enforced as soon as sign-off of the plan is completed. Resources including personnel and equipment necessary to comply with the procedures must be made available with the rollout of the plan. Implementation should include considerations for communications of the protocols and training of all relevant personnel, as well as training programs being available for new employees.

Monitoring and review

This step involves continued monitoring and auditing of the plan to ensure that the control measures remain effective. The plan should also be reviewed periodically to ensure that changes in conditions can be incorporated into the plan. These changes will require signoff from all the relevant stakeholders (Kennedy and Tyson, 2001).

CHAPTER 3 - METHODOLOGY



3. METHODOLOGY

3.1. Introduction

This study will aim to formulise recommendations that will assist in identifying potential reactive ground areas and safely managing these areas when encountered. The method of this study includes the investigation of a case study at Goedgevonden Colliery in the Witbank Coalfields area of South Africa. The current controls for reactive ground will be evaluated and recommendations from various reports and studies will be included to determine the most favourable processes to follow with regards to the management of reactive ground at Goedgevonden, and sites with similar conditions. The purpose of this research report will thus be to correctly manage reactive ground conditions in opencast coal mines in the specified study area.

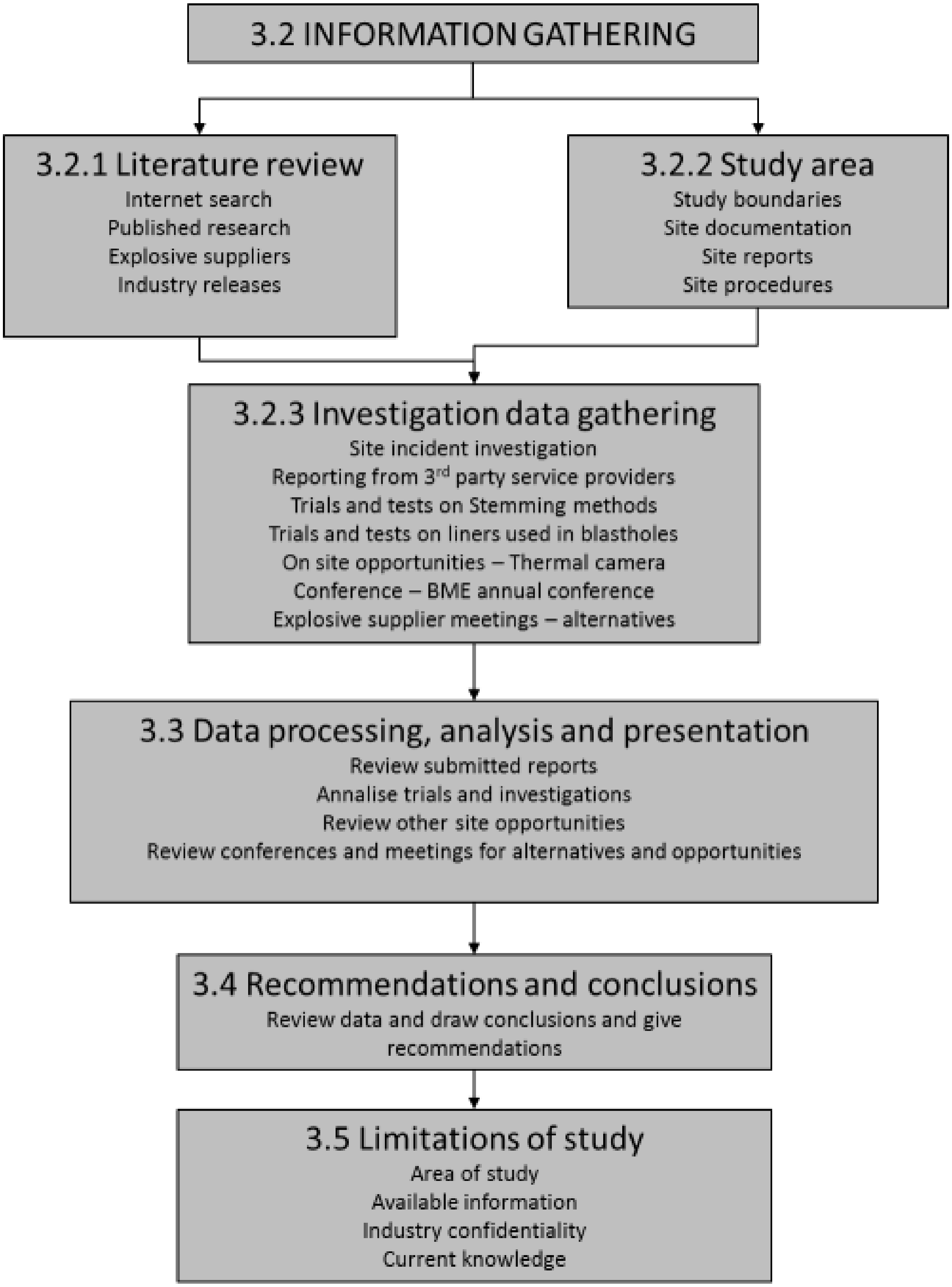


Figure 3: Flow diagram of the methodology process of the study (Produced by Botha, 2013)

3.2. Information Gathering

3.2.1. Literature review

A reactive ground blasting incident occurred at Goedgevonden Colliery on the 21st of October 2010. From the date of the incident to the time this research report was prepared, data has been gathered to understand, monitor and manage possible reactive ground conditions on the regions' coal mines.

To completely understand reactive ground and the way in which it can be treated or managed, information had to be gathered from all available sources. With many similarities and industry confusion between spontaneous combustion and reactive ground, the first step of the research had to cover the main differences between spontaneous combustion and reactive ground. The focus was then moved to reactive ground and aimed to gather useable data concerning the factors influencing the reactivity of materials, how explosives react in this ground, how it can be identified, and how reactive ground should be managed on site.

Communications with peers in the mining industry was made to gather available documentations regarding the research subject. Electronic formats of these documents were obtained for review.

Explosive suppliers dealing with the affected mine group were contacted and a request for information and assistance regarding the reactive ground phenomenon was made. Several documents concerning the suppliers' products and research on their products were made available for this study.

Published research regarding reactive ground was gathered through the University of the Witwatersrand. In addition to this, research through the World Wide Web was done to complete identified gaps in several sections of the research paper when no other published research through normal communication lines were successful.

The information from these papers, reports and procedures was studied for the understanding of the subject matter and assisted in the formulation of risk mitigating management processes going forward. The study material list is included in the reference list in this report.

3.2.2. Study area

As mentioned, the study area identified in the research is the mine Goedgevonden Colliery, where the previously noted reactive ground incident took place. Information regarding the site was readily available and knowledge of the mining operation was well understood. This assisted in the investigation and understanding of the problems and possible solutions. Free access to the mining pit was allowed, and the mine was willing to assist with the study in reactive ground.

The Republic of South Africa, Department of Minerals and Energy, Mine Works Plan for Goedgevonden Colliery (2006) and the Republic of South Africa, Department of Minerals and Energy, Environmental Management Program (2002), submitted to the then named Department of Minerals and Energy, was used to understand the background of the mining operation. With basic assumptions for the mining methods and information from the mining models used to calculate the Life of Mine plans, an understanding for the exposure and extraction methods could be formulated.

The drilling and blasting processes on the mine have been in operation since 2007, and was developed with industry specialists and experience in the conditions found on and around the site. These processes are described in this report as they were performed at the time of the study.

3.2.3. Investigation data gathering

The research done on site was based on findings of work done either by presentation of test data to the mine, or by physical testing of possible controls when dealing with reactive ground.

An on-site team completed a preliminary investigation of the reactive ground incident. The mine requested the explosive supplier to investigate and report on the incident. Their report was then made available for further interpretation on site.

A third party laboratory was used to test and analyse samples taken from the incident site and confirm reactivity of the host rock in the vicinity of the incident. A positive test from the laboratory would then have confirmed that the study was indeed focussed in the right direction where reactive ground was regarded as the main contributor to the incident.

From the information gathered in the literature review and the preliminary investigations, tests were proposed to see if some of the processes currently applied on the site were adequate, or can be improved upon. Physical cycle time studies were done with regards to the stemming method used when the previously mentioned incident took place, the cycle times of a Skid Steer loader was recorded and can be seen in **Appendix A.** Additionally, comparative time studies were done with an alternative stemming delivery system, as recorded in **Appendix B**. The results are described further in Section 5.5. Blast hole liners were already in use on the site, which were primarily used in presplit blasting. As mentioned in the literature review **(Section 2.2.6.9),** it was investigated to conclude whether the liners could be considered as an option when preparing a blast in reactive ground. Refer **Section 5.6** for the results and discussion. The geology department of the mining site has a thermal imaging camera available for use in the operational pit, and the possibility of using the equipment in assisting with reactive ground management is investigated in **Section 5.7** and physically tested.

The annual BME Conferences (2011, 2012, and 2013) were attended to gather information with regards to blasting research and possible work on reactive ground. The 2013 conference hosted some speakers that were actively busy working and dealing with reactive ground globally. The conference papers were made available for further study and used to formulate possible solutions and ways to mitigate risk when working in reactive ground as discussed in **Section 5.8.**

The current (2013) initiating system supplier to the study area (AEL), proposed a new product that can detect a rise in temperature in a blast hole and warn the personnel working on the blast block. The use of these “Blast eye monitors” was introduced for use on suspected reactive ground as an early warning system and is described fully in **Section 5.9** of this study.

With the inception of the “Blast eye monitor”, the question of the alarms by the monitor at 60°C and at 80°C was raised. Temperature tolerances were reviewed of the most common initiating systems supplied to the coal mining industry by AEL to understand the reasoning behind the specific temperature alarms. The supplier presented the information contained in their product catalogue and is presented in **Section 5.10.**

3.3. Data processing, analysis and presentation

The data found in all the information gathered has been interrogated and interpreted in this research report. Pertinent information was presented to indicate critical findings and to assist with the interpretation of the various sources. As the study continued various photos were taken of sections in question and these are presented in the research report. The findings in each section of the research results are presented and discussed to understand any possible shortcomings or opportunities that may be available for the management of the studied risk.

The on-site testing of the stemming methods is discussed in **Section 5.5**. Appendices are included showing time studies done during this specific study. The study may be influenced by different operators and conditions, but a general idea of the loading times can be evaluated and discussed.

Physical testing of the liners as done at the study site is discussed in **Section 5.6**, and conclusions from visual inspections were made regarding the use of liners to insulate the explosive from reactive ground.

The use of a thermal imaging camera was tested by conducting physical field tests. Temperate variances can be recorded and investigated for differences / inconsistencies to assist with identifying risk areas. The camera was also used to assist in the measuring of test samples, as well as surface temperatures on blast blocks at various stages of the drilling and charging processes.

The presented “blast eye monitor” information was recorded and discussed as an option and recommendations drawn from the demonstrations are included in the report. From the information supplied by the initiating systems supplier, relevant data could be extracted to indicate the product temperature sensitivity and conclusions can be drawn with regards to the current products used on the study area.

3.4. Recommendations and conclusions

From the literature review, the research of the study area, the information gathering regarding the case study and the analysis throughout the research report, recommendations and conclusions have been made. These recommendations are listed and presented to be available for readers to apply, when necessary, to current practices throughout the coalfields workings. The conclusions are based on the understanding of reactive ground as developed throughout the study and compilation of this research report.

3.5. Limitations of study

The research in this study is based on the information that was readily available to the researcher. The work done in the study is done around the study area, and even though the Witbank Coalfields are quite homogenous throughout with regards to the geology, some major changes may be observed at other coal mining sites in the vicinity. Therefore, the results are based only on the study site.

It is possible that other work currently done in the industry may shed more light on certain subjects and investigation points in this study. It is thus essential, as recommended in the Chapter 6, that a continued review of the procedures is done, and possible improvements should be investigated to continuously improve the procedures regarding reactive ground, and to continuously reduce the risk imposed on the mine when experiencing reactive ground.

Specific limitations with regards to the research and results findings:

- Stemming loading review and trials: limited field trials as well as variances in operators and conditions may influence and introduce variances to the total cycle times.
- Testing of liners for insulation from reactive ground: only products from two suppliers were tested. Other options may be available in the current market, that are not included in the study, and these products may prove to provide a better result when tested.
- Initiating systems studied only include products from current suppliers to the study area.

CHAPTER 4 – STUDY AREA

4. STUDY AREA

4.1. Location of case study mine

Goedgevonden Colliery is a Glencore mine located within the jurisdiction of the eMalahleni Local Municipality, in the Mpumalanga Province of South Africa. The mine is situated approximately 50km southeast from the town of eMalahleni, previously known as Witbank. The closest town to the colliery is Ogies town, approximately 5km east from the main offices of Goedgevonden Colliery. Various farm communities and private institutions surround the mine.

The **green star** in **Figure 4** and **Figure 5** indicates the location of the mine with regard to the surrounding towns and within Southern Africa. Coal is fed from the mine per rail and road to various coal fired power stations, and transported per rail to the Richards Bay Coal Terminal for export to overseas markets.

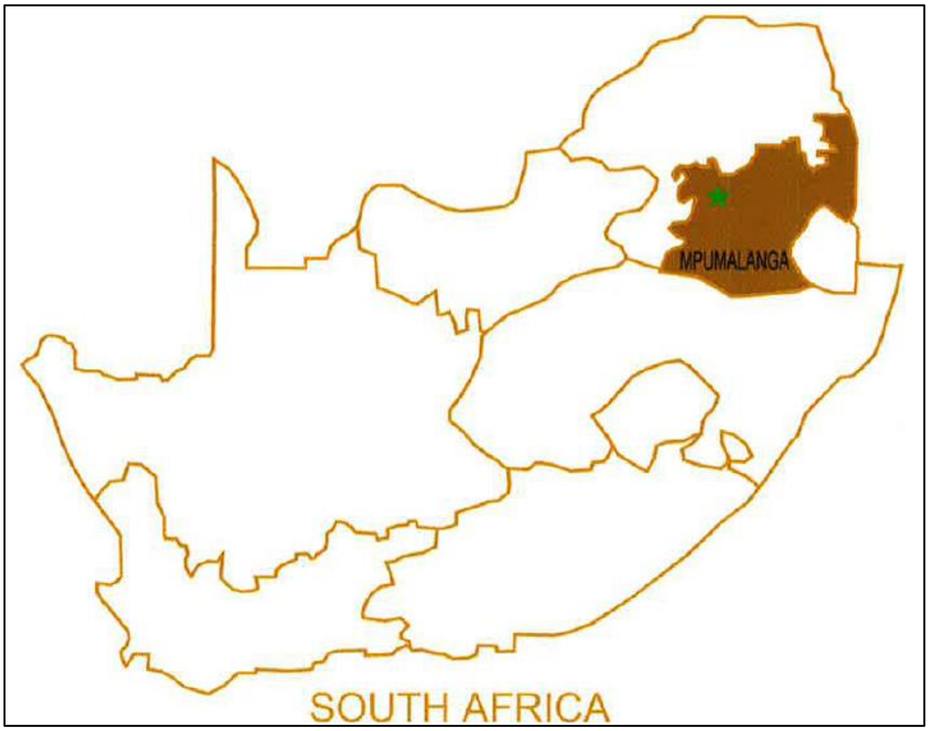


Figure 4: Location of Goedgevonden Colliery in relation to South-African borders (Mine Works Plan Goedgevonden Colliery 2006)

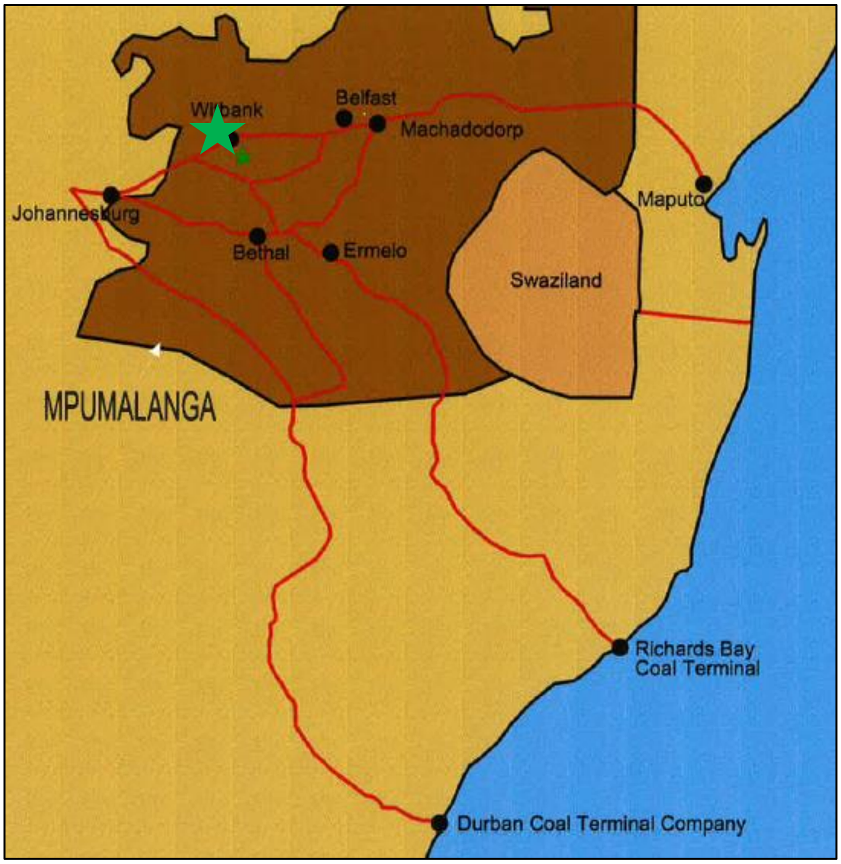


Figure 5: Goedgevonden Colliery in relation to major towns and ports (Mine Works Plan Goedgevonden Colliery 2006)

4.2. Background of the case study mine

4.2.1. History and mining methods of the mine

The Environmental Management Program for Goedgevonden Colliery was approved by the Department of Minerals and Energy on 27 February 2002 (DME OT6/2/2/448, 2002). The mine plan was originally designed to mine 90% of the reserve using underground coal mining methods. The underground mining method chosen was Bord and Pillar mining, in which only the higher grade lower part of the number 4 and number 2, coal seams would be mined, i.e. the lower 3-3.5m of the available 6m coal seams. The remainder of the mine reserve would be excavated using Opencast Truck and Shovel coal mining which would establish access to the underground reserves.

No mining activities commenced before a take-over from Xstrata Coal South Africa (XCSA) late in 2002. New feasibility studies done on the Goedgevonden Reserve indicated that the reserve may be better suited to opencast mining, as described in the 2006 approved Mine Works Plan (Mine Works Plan Goedgevonden Colliery, 2006).
Large scale opencast mining commenced on the Farm Goedgevonden, under the Banner of Goedgevonden Colliery, Xstrata Coal South-Africa.

Geological disturbances don't affect opencast mining operations to the same extent as underground mining, the major impact being the coal recovery. At Goedgevonden there is a "no coal" area (Pre-Karoo) within the boundary of the main pit.

4.2.2. Regional geology and geological structure of the reserve

As per the description in the 2006 approved Mine Works Plan, Goedgevonden Colliery is located near the southern part of the Witbank Coalfields which is defined by Pre-Karoo granite and felsite hills. The area on surface comprises of relatively flat farm land, intersected throughout by wetlands. From interpretation of the borehole data in the Goedgevonden reserve, no major faults or structural disturbances were detected other than a Pre-Karoo Basement high that exists in the southern region of the reserve. All coal seams present terminate against the Pre-Karoo high. The seams climb as they lap onto the Pre-Karoo high and this causes steep dips of the seams around that area.

The coal deposits are all contained within the Karoo Sequence. In the Witbank Coalfield the coal seams are numbered from the number 1 Seam at the base up to the number 5 Seam at the top of the sequence and closest to the surface. Each coal seam is hosted in a sequence of mudstone, siltstone and sandstone. All five coal seams are present in the Goedgevonden Colliery Reserve.

The Number 1 and 3 Seams are not currently mined and hence, not included in the mineable reserve due to their poor quality and low seam thickness (Mine Works Plan, Goedgevonden Colliery, 2006).

The Number 2 Seam is extensively developed throughout the reserve and consists of a basal bright band overlain by lustrous to dull lustrous coal with thin bright bands. The Number 4 Seam in not as extensively developed as the Number 2 Seam due to it being closer to the surface and more influenced by weathering. It consists of a basal bright band overlain by a zone of dull and dull lustrous coal with thin bands and carbonaceous shale/mudstone partings. The number 5 Seam is preserved as erosional remnants on the higher ground. It consists of a bright, well-banded, vitrain rich coal.

Tables 1 to 5 taken from the Goedgevonden Mine Works Plan (2006) indicate the type of coal and expected qualities found in the coal reserve.

Table 1: Summary of the Number 2 Select seam (After Goedgevonden Mine Works Plan, 2006)

Summary of the number 2 Select seam								
No. 2S Seam								
	Depth	Thickness	RD	Moisture	Ash	Volatiles	Sulphur	CV
	(m)	(m)		%	%	%	%	MJ/kg
Minimum	10.3	0.7	1.4	1.9	11.5	3.8	0.2	12.4
Maximum	103.1	6.1	1.9	4.7	53.5	32.7	3.3	28.1
Average	46.8	3.6	1.6	3.3	24.4	23.4	1.3	23.1
Current mining	35.5	2.7	1.4	3.2	21.6	18.8	1.2	22.6

Table 2: Summary of the Number 2 Top seam (After Goedgevonden Mine Works Plan, 2006)

Summary of the number 2 Top seam								
No. 2T Seam								
	Depth	Thickness	RD	Moisture	Ash	Volatiles	Sulphur	CV
	(m)	(m)		%	%	%	%	MJ/kg
Minimum	15.1	0.3	1.5	1.7	11.6	3.5	0.1	3.9
Maximum	101.7	6.8	2.2	4.6	76.4	46.9	6.9	25.6
Average	44.2	2.7	1.7	3.0	39.1	18.8	1.1	16.9
Current mining	35.5	1.9	1.6	3.4	23.8	14.1	1.2	20.9

Table 3: Summary of the Number 4 Select seam (After Goedgevonden Mine Works Plan, 2006)

Summary of the number 4 Select seam								
No. 4S Seam								
	Depth	Thickness	RD	Moisture	Ash	Volatiles	Sulphur	CV
	(m)	(m)		%	%	%	%	MJ/kg
Minimum	5.8	0.6	1.4	1.8	14.9	9.6	0.2	6.6
Maximum	89.0	6.6	1.8	6.9	70.1	33.0	5.2	25.8
Average	28.1	2.9	1.6	3.5	25.2	23.4	1.3	22.6
Current mining	16.2	2.2	1.4	3.7	23.4	21.3	2.0	21.1

Table 4: Summary of the Number 4 Top seam (After Goedgevonden Mine Works Plan, 2006)

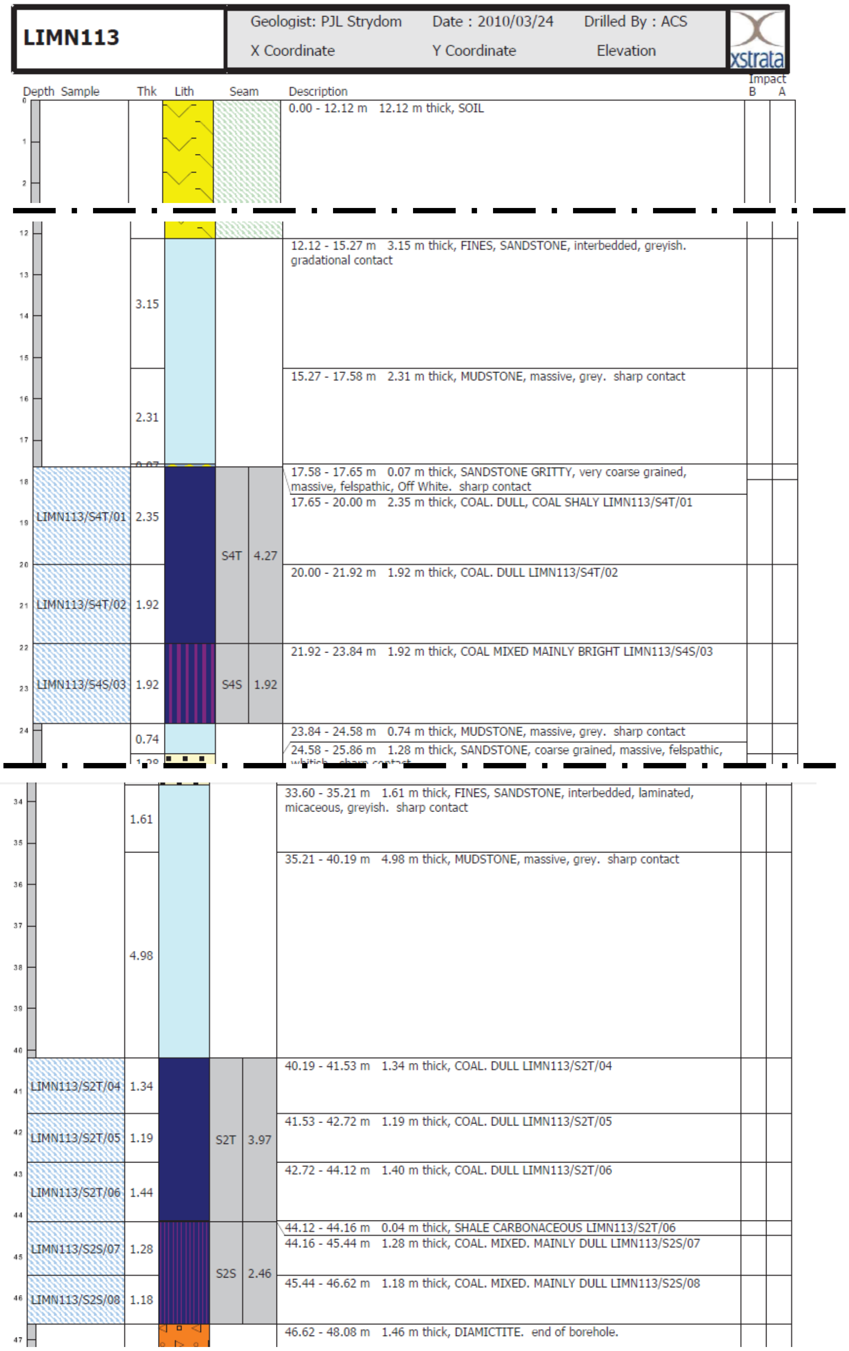
Summary of the number 4 Top seam								
No. 4T Seam								
	Depth	Thickness	RD	Moisture	Ash	Volatiles	Sulphur	CV
	(m)	(m)		%	%	%	%	MJ/kg
Minimum	3.6	0.3	1.4	0.4	13.8	3.4	0.3	3.0
Maximum	86.9	6.8	2.5	7.5	79.0	27.7	5.1	26.9
Average	25.7	2.8	1.7	3.0	39.7	19.9	1.3	16.9
Current mining	16.3	2.7	1.6	2.6	23.8	19.2	1.2	16.5

Table 5: Summary of the Number 5 seam (After Goedgevonden Mine Works Plan, 2006)

Summary of the number 5 seam								
No. 5 Seam								
	Depth	Thickness	RD	Moisture	Ash	Volatiles	Sulphur	CV
	(m)	(m)		%	%	%	%	MJ/kg
Minimum	5.2	0.3	1.4	2.2	11.7	17.0	0.3	4.9
Maximum	73.6	3.0	1.8	6.5	44.4	32.9	3.5	28.0
Average	25.8	2.0	1.5	3.7	23.5	27.1	1.4	23.4
Current mining	13.5	1.8	1.5	4.1	14.7	30.7	0.5	24.0

Figure 6 indicates a borehole log of Goedgevonden Colliery in the current working area. This borehole was sampled close to the reactive ground incident recorded at Goedgevonden Colliery. The incident took place when the hard sandstone, mudstone waste band was drilled and blasted in order to expose the 4 Seam coal. It is believed

that the hard material above the 4 Seam coal band contained the reactive sulphides that led to the incident. Sulphur leaching into the overlaying host rock is further described in Chapter 5, **Section 5.4**.



LIMN113

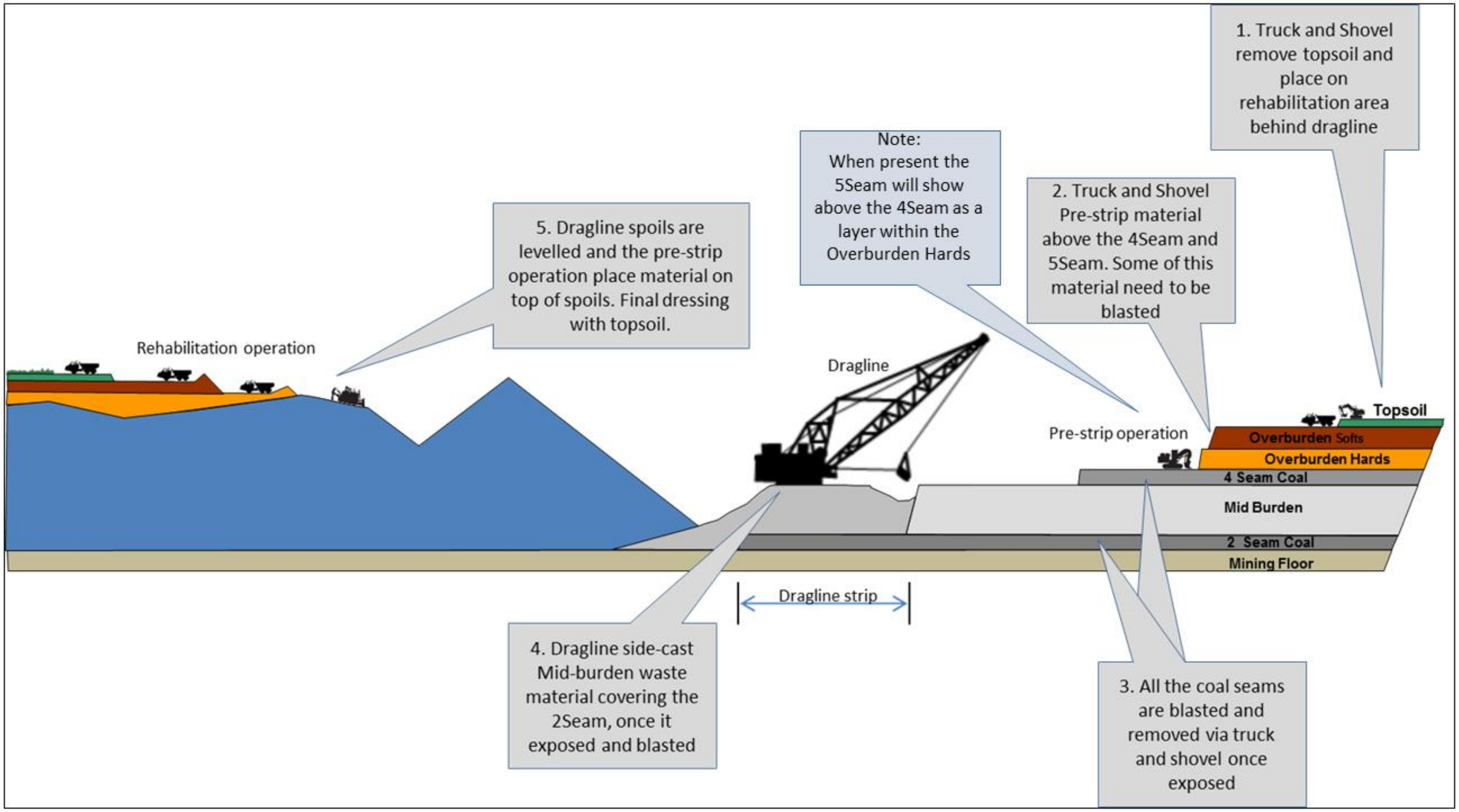
Geologist: PJL Strydom
Date : 2010/03/24
Drilled By : ACS
X Coordinate
Y Coordinate
Elevation

Sample	Thk	Seam		Description
				0.00 - 12.12 m 12.12 m thick, SOIL
	3.15			12.12 - 15.27 m 3.15 m thick, FINES, SANDSTONE, interbedded, greyish. gradational contact
	2.31			15.27 - 17.58 m 2.31 m thick, MUDSTONE, massive, grey. sharp contact
	0.07			17.58 - 17.65 m 0.07 m thick, SANDSTONE GRITTY, very coarse grained, massive, felspathic, Off White. sharp contact
LIMN113/S4T/01	2.35	S4T	4.27	17.65 - 20.00 m 2.35 m thick, COAL. DULL, COAL SHALY LIMN113/S4T/01
LIMN113/S4T/02	1.92			20.00 - 21.92 m 1.92 m thick, COAL. DULL LIMN113/S4T/02
LIMN113/S4S/03	1.92	S4S	1.92	21.92 - 23.84 m 1.92 m thick, COAL MIXED MAINLY BRIGHT LIMN113/S4S/03
	0.74			23.84 - 24.58 m 0.74 m thick, MUDSTONE, massive, grey. sharp contact
	1.28			24.58 - 25.86 m 1.28 m thick, SANDSTONE, coarse grained, massive, felspathic, whitish. sharp contact
	1.61			33.60 - 35.21 m 1.61 m thick, FINES, SANDSTONE, interbedded, laminated, micaceous, greyish. sharp contact
	4.98			35.21 - 40.19 m 4.98 m thick, MUDSTONE, massive, grey. sharp contact
LIMN113/S2T/04	1.34	S2T	3.97	40.19 - 41.53 m 1.34 m thick, COAL. DULL LIMN113/S2T/04
LIMN113/S2T/05	1.19			41.53 - 42.72 m 1.19 m thick, COAL. DULL LIMN113/S2T/05
LIMN113/S2T/06	1.44			42.72 - 44.12 m 1.40 m thick, COAL. DULL LIMN113/S2T/06
				44.12 - 44.16 m 0.04 m thick, SHALE CARBONACEOUS LIMN113/S2T/06
LIMN113/S2S/07	1.28	S2S	2.46	44.16 - 45.44 m 1.28 m thick, COAL. MIXED. MAINLY DULL LIMN113/S2S/07
LIMN113/S2S/08	1.18			45.44 - 46.62 m 1.18 m thick, COAL. MIXED. MAINLY DULL LIMN113/S2S/08
				46.62 - 48.08 m 1.46 m thick, DIAMICTITE. end of borehole.

Figure 6: Borehole log of Goedgevonden Colliery mining reserve (Taken from Goedgevonden Geological Database, 2010)

4.3. Description of the mining operation

Figure 7 indicates the physical mining process as currently practiced at Goedgevonden Colliery.



1. Truck and Shovel remove topsoil and place on rehabilitation area behind dragline

2. Truck and Shovel Pre-strip material above the 4Seam and 5Seam. Some of this material need to be blasted

Note: When present the 5Seam will show above the 4Seam as a layer within the Overburden Hards

5. Dragline spoils are levelled and the pre-strip operation place material on top of spoils. Final dressing with topsoil.

4. Dragline side-cast Mid-burden waste material covering the 2Seam, once it exposed and blasted

3. All the coal seams are blasted and removed via truck and shovel once exposed

Figure 7: General Section of GGV Opencast methodology (Produced by Botha, 2009)

As mentioned, Goedgevonden Colliery is an Opencast Dragline Operation assisted with Truck and Shovel Pre-strip mining. Opencast mining is a method applied to extracting a tabular resource that is found close to the surface. The layer of waste burden above the valuable deposit is comparatively thin and can be removed economically away from the desired resource. An opencast mine is defined by backfilling of spoils immediately behind the mining operation. The removal of overburden is usually distinct from the coaling operation and if multiple seams are to be mined benches are created to mine the individual seams.

As seen in **Figure 7**, the flat part of the step in an opencast mine is called the bench. The benches currently vary from 3m to 23m in burden thickness, dependent on the mining equipment's capacity. The bench thickness will also rely on the size of machinery allocated to the specific bench and the safe reach the machine can handle.

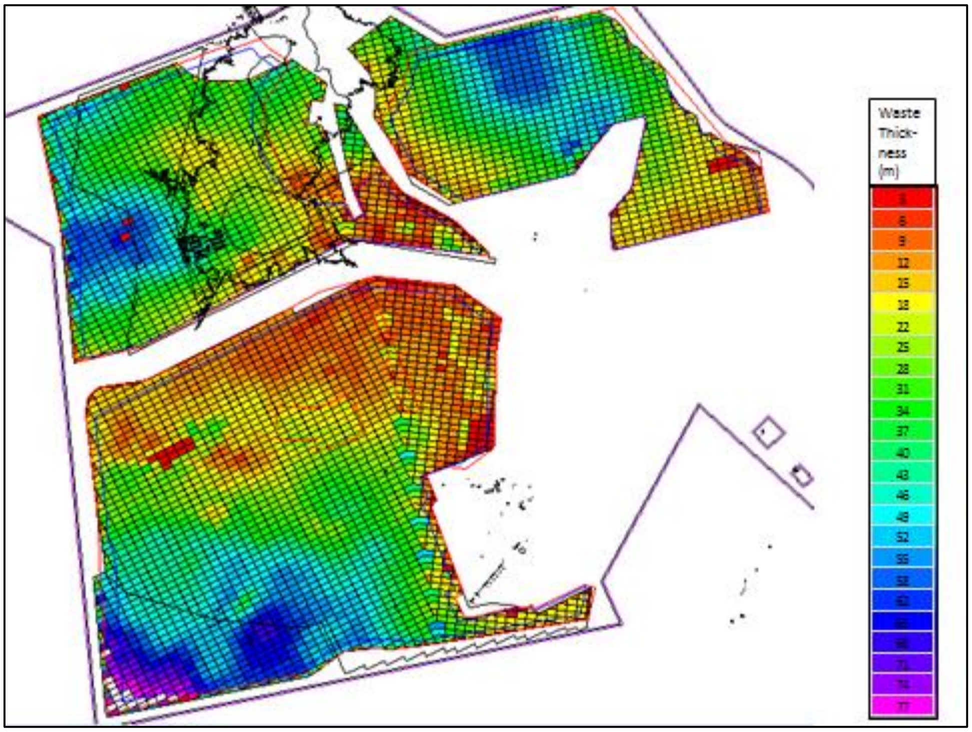


Figure 8: Burden thickness of Truck and Shovel Waste above coal at Goedgevonden Colliery (Taken from Goedgevonden Reserve model, 2013)

The number 5 Seam coal and the number 4 Seam coal is exposed via the Truck and Shovel Operations. The Number 2 Seam coal is then exposed using dragline side cast. The coal is then extracted with a Truck and Shovel operation and processed through the Goedgevonden washing plant to serve the Export and local Eskom market. The planned production output of the mine is an average of 12Mt of Run of Mine (ROM) coal per annum. This is based on the stripping capacity of the 60 cubic meter capacity Dragline (BE1570).

A waste Truck and Shovel fleet remove burden with one 25m^3 cubic meter Hydraulic shovel (EX5500), two 17m^3 cubic meter Hydraulic shovels (EX2500) and 150 – 190 tonne capacity dump trucks (785 and 789 CAT trucks). The operation is undertaken such that the Truck and Shovel waste operation will dump on the disturbed side to accomplish a levelled area for rehabilitation. Refer to **Table 6.**

Table 6: List of the Goedgevonden production equipment and rates as per the Life of Mine Schedule (Produced by Botha, 2013)

PROCESS	EQUIPMENT	RATES
Topsoil	EX870 Excavator and articulated dump trucks	10 m3/hr
Truck and Shovel Pre-strip Fleet	EX5500 Hydraulic Shovel and 789 Dump trucks	1150 m3/hr
	EX2500 Hydraulic Shovels and Excavators with 785 Dump trucks	600-700 m3/hr
Burden (up to 7m) drilling	DM30 rotary drills	45-60 m/hr
Burden (deeper than 7m) drilling	PV275 Rotary Percussion drills	45-60 m/hr
Waste Parting between above 2Seam	BE1570W Dragline	2150 m3/hr
Coal drilling	DM30 rotary drills	45-60 m/hr
Coal Loading and hauling	EX2500 Hyraulic Excavator, WA1200 and 993K wheel loaders	1000 - 2000 t/hr

4.4. Description of the blasting operation

Most of the burden material above the coal seam is drilled and blasted to fragment the material enough for loading with the various diggers and shovels. The drilling and blasting parameters have evolved from the inception of mining activity on Goedgevonden Colliery through trials, consultation and adjustments through experience of the ground conditions. The following is an overall description of the current blasting parameters that has been tried and tested on site. An effort was made to keep the parameters as simple and generic as possible. By doing this it allows easier workflow for the blast crew and only significant changes in the physical mining conditions will warrant special instructions. All blasting is currently being done by pyrotechnic initiation. This is cheaper than the electronic alternative and to date has achieved the desired fragmentation.

4.4.1. Interburden Blasting – Pre-split

The mid-burden, or interburden parting between the 4 Seam and 2 Seam coal is stripped by dragline. The blast profile and fragmentation need to remain constant to allow the dragline to setup its digging sequence and maintain that sequence throughout the strip with no major changes from one blast profile to the next. Any such changes will require additional preparation work for the dragline and thus slow down the rate of advance, hence slowing down the coal exposure. The current blast profile and fragmentation is as follows:

- The current strip width is 65m (refer to **Figure 7**).
- All drilling is done using 251mm diameter holes.
- A pre-split line is drilled that defines the 65m strip with a smooth high-wall. The pre-split line has the following characteristics:
    - Pre-split holes are drilled 3m apart on the 65m strip line using the 251mm diameter drill.
    - The pre-split holes are drilled through the mid-burden or interburden parting and 2 Seam coal in order to assist coal extraction up to the high-wall.
    - The pre-split crack formed after the pre-split blast also assists in draining excess water from the pattern drilling and blasting to follow, as can be seen in **Figure 9**.
    - Using Sleeves to position the explosive charge in the hole, two separate charges are set in the hole as per the blast design (**Figure 10**).

- To achieve a blast as close to instantaneous as possible using pyrotechnic initiation, 10g Cord is used in the tie-up to a 400g booster (**Figure 10** and **Figure 11**).

Figure 9: A pre-split hole after blast showing the split or crack formed (Photo taken by Botha, 2010)

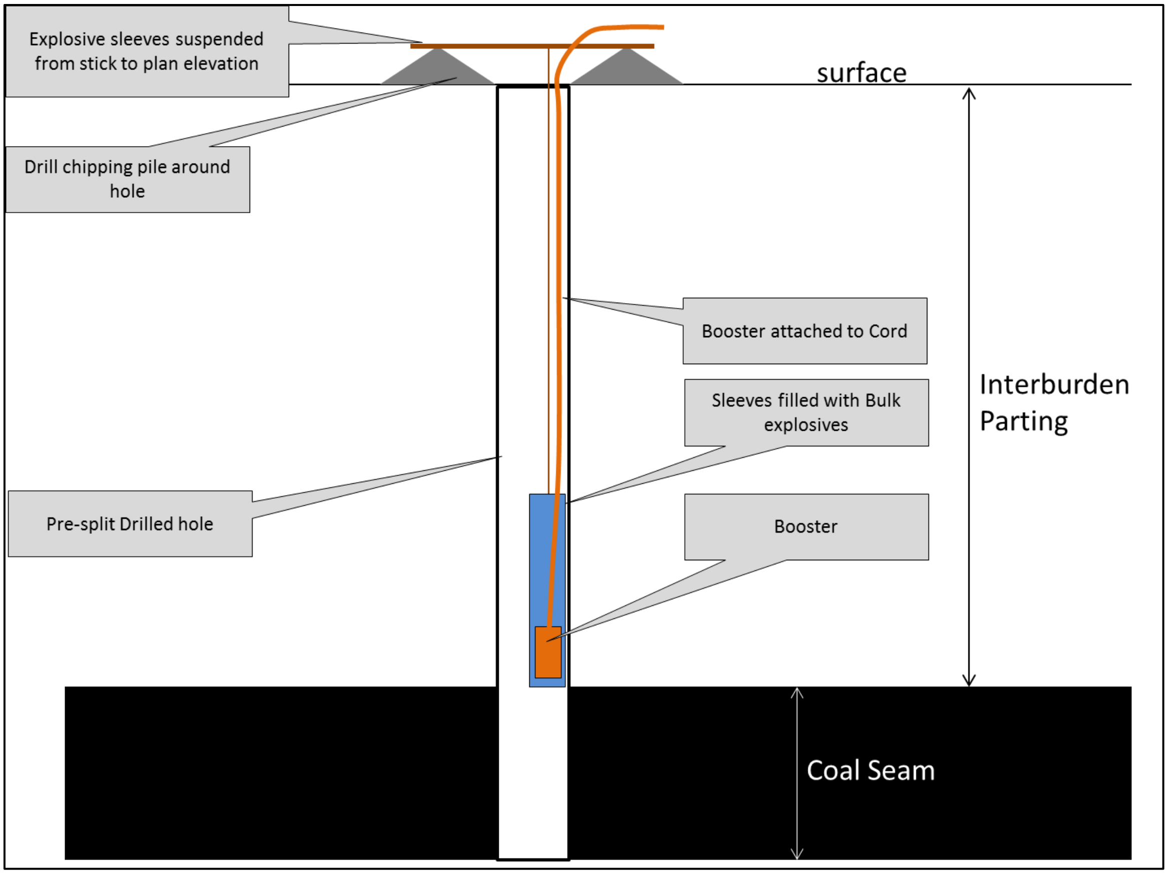


Figure 10: Section indication typical charging of pre-split holes (Produced by Botha, 2013)

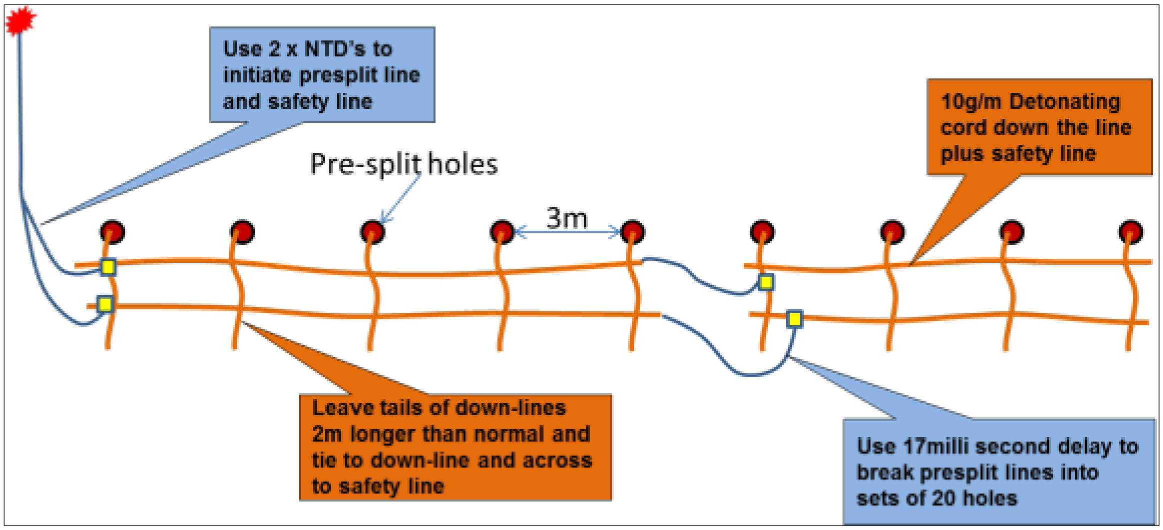


Figure 11: Top view schematic of typical tie-up of a Pre-split blast (Produced by Botha, 2013)

Figure 12: Pre-split tie-up on surface with a single charge suspended into the blast hole (Photo taken by Marton, 2010)

4.4.2. Interburden Blasting – Infill

Once the pre-split is blasted the Interburden infill need to be blasted. This is done as follows:

- Fragmentation is required for allowing the loading with a 60m^3 bucket capacity Dragline. (Refer to **Section 4.3**, Description of mining operation).
- In order to achieve the correct fragmentation, the Powder Factor (PF) (Ratio of bulk explosive kilogram to the cubic metre material being blasted) for the Interburden material range from 0.65 up to 0.80 depending on the thickness of the interburden parting as well as the hardness of the material. The average planned PF for the Interburden is 0.75.

- The pattern holes are drilled with a 251mm diameter drill hole at a 3m offset from the pre-split line, as seen in **Figure 12.** The first line next to the pre-split will be named the A-line holes, through the alphabet as the lines progress away from the pre-split.
- The pattern lines are then drilled with a 7m burden (**Figure 12**) between the lines and 9m spacing between the holes in the lines.
- The pattern holes are staggered to maximise the area of influence for every hole.
- Holes need to be backfilled to the designed coal depth to minimise coal damage and dilution with waste material.
- The A-line holes receive a lesser charge to soften the impact on the top edge of the blast (**Figure 13**).
- Gasbags need to be placed into the holes at designed depth to allow proper gassing of the explosives and keep the explosive undiluted with stemming (**Figure 14**).
- 400g Boosters initiate the bulk explosives through pyrotechnic delayed detonators and timed to leave the blast profile to the desired design for optimal dragline digging (**Figure 14** and **Figure 15**).

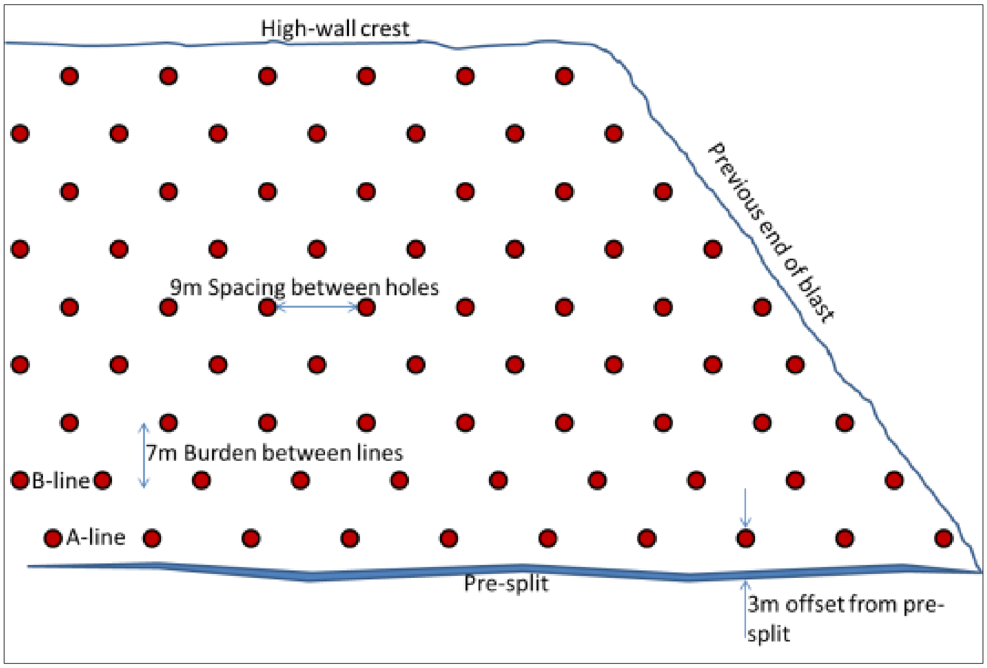


Figure 13: Top view of typical Interburden pattern (Produced by Botha, 2013)

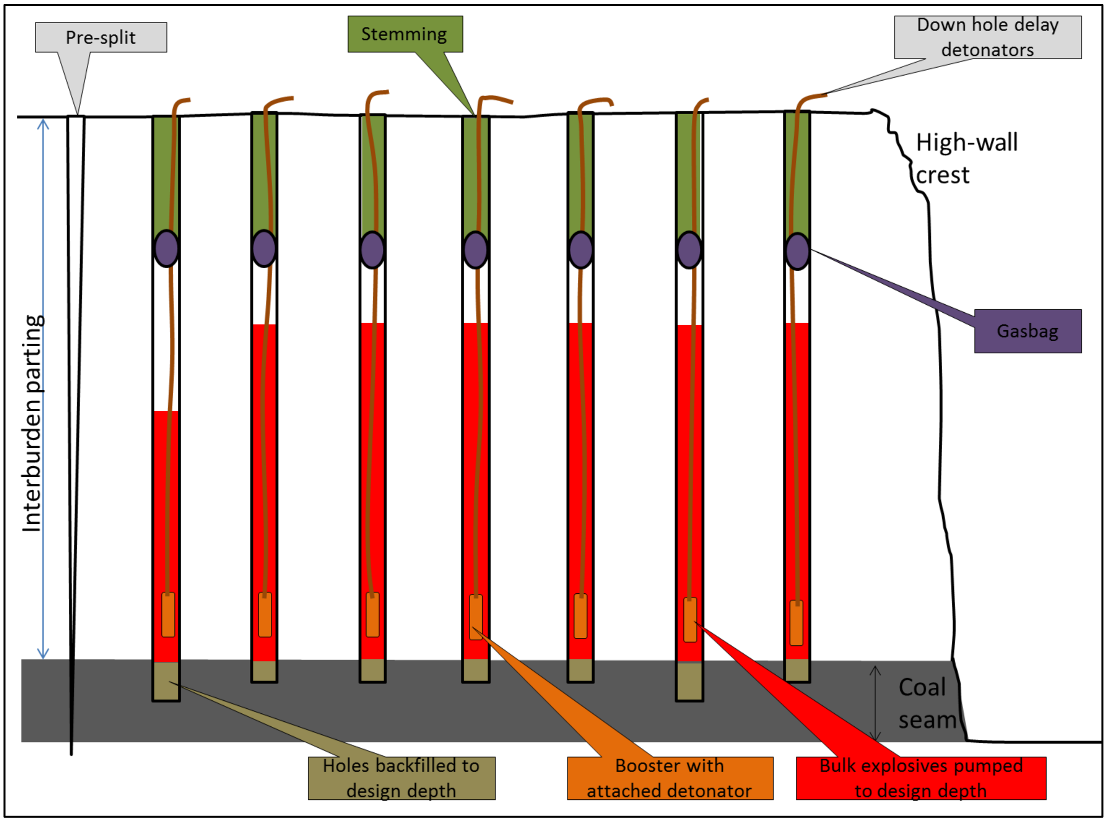


Figure 14: Sectional schematic (not to scale) of Interburden charging of blast holes (Produced by Botha, 2013)

Figure 15: Photo of Interburden cast blast to be moved by dragline (Photo taken by Botha, 2013)

4.4.3. Overburden Blasting

Overburden blasting requires a much finer fragmentation. The equipment loading the material has bucket capacities ranging from 15m^3 to 25m$^{\mathbf{3.}}$ (Refer to **Section 4.3**, Description of mining operation). **Figure 18** shows a photo of the overburden blasting preparations as done at the site. The process for overburden blasting is as follows:

- No pre-split on overburden blasting operations.
- The PF for the blasting of the overburden is set between 0.45 and 0.55kg/m^2.
- A burden of 5m and spacing of 5m (with 251mm diameter holes) is used and drilled in a staggered pattern.
- Holes need to be backfilled to the designed coal depth to minimise coal damage and dilution with waste material.
- Gasbags need to be placed into the holes at designed depth to allow proper gassing of the explosives and keep the explosive undiluted with stemming (**Figure 16**).
- 400g Boosters initiate the bulk explosives through pyrotechnic delayed detonators and timed to leave the blast profile with minimum movement for optimal digging for the truck and shovel fleets (**Figure 17**).

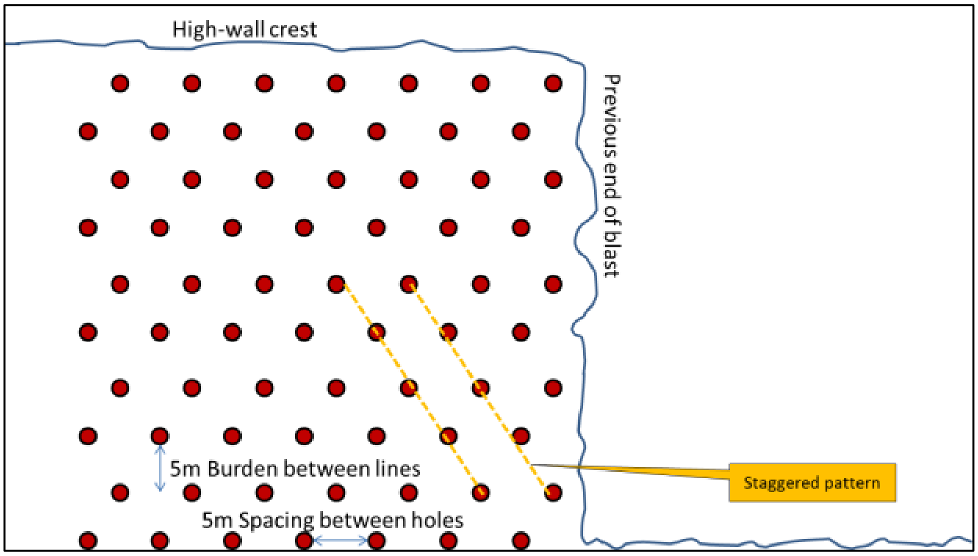


Figure 16: Top view (not to scale) of typical overburden pattern (Produced by Botha, 2013)

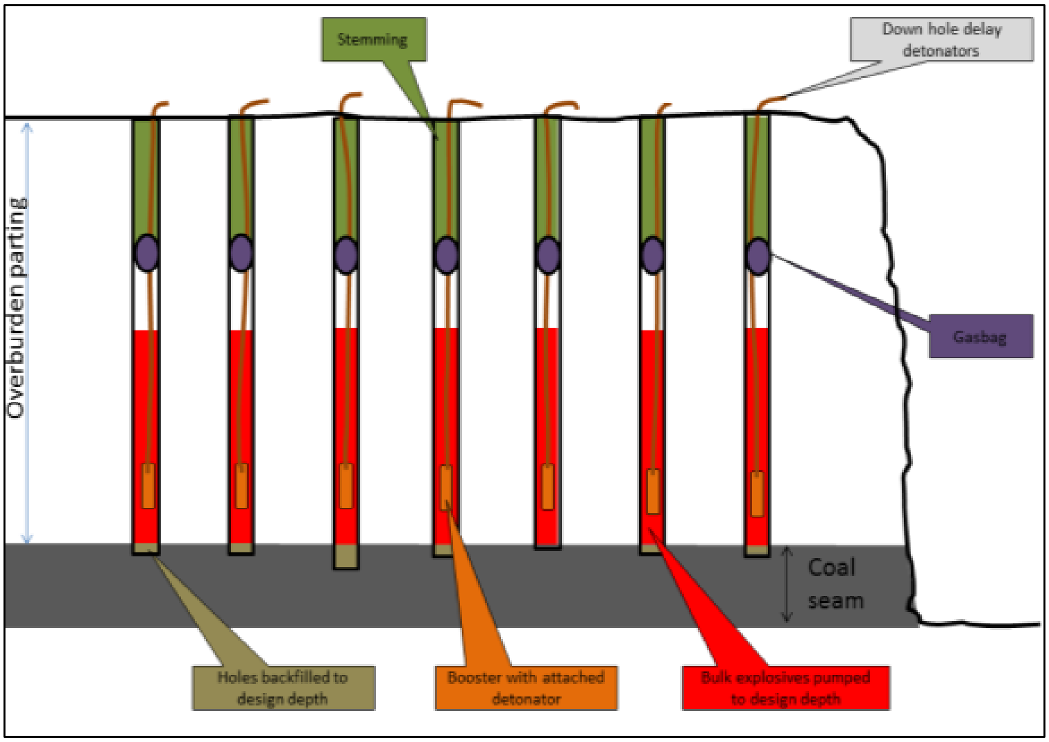


Figure 17: Sectional schematic (not to scale) of overburden charging of blast holes (Produced by Botha, 2013)

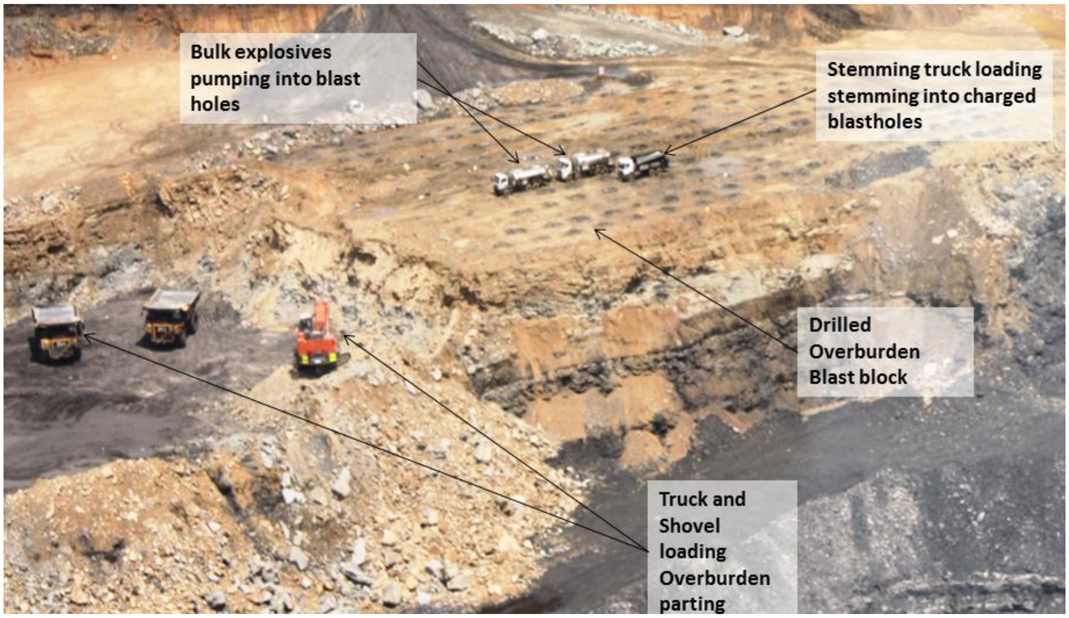


Figure 18: Photo of Overburden Blast preparation (Photo taken by Botha, 2013)

4.4.4. Coal Blasting

Coal only needs a relatively small charge compared to the more competent Over- and Interburden material. The equipment loading coal has bucket capacities ranging from 15m^3 to 25m^3. (Refer to **Section 4.3**, Description of mining operation). Coal blasting procedures can be summarized as follows:

- The PF for coal is dependent on the quality of the coal being blasted. The higher quality more brittle coal will be blasted at a PF of as low as 0.20 (kg/m^3) and can range up to 0.38 (kg/m^3) for the lowest quality coal.
- A burden of 5m and spacing of 5m is used and drilled in a staggered pattern.
- 142mm diameter holes are drilled for coal blasting.
- A gasbag placed high in the hole with, a small amount of drill chippings as stemming completes the preparation of the holes.
- 150g Boosters initiate the bulk explosives through pyrotechnic delayed detonators and timed to leave the blast profile with minimum movement for optimal digging for the truck and shovel fleets.

The coal schematic is similar to **Figure 16** and **Figure 17** as with the overburden charging.

4.4.5. Blasting Volumes and rates

Table 7: Blasting requirements for Goedgevonden planned production 2014 (Goedgevonden Life of Mine Plan, 2013)

Descriptions		Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14	Total
Blasting Volumes														
Interburden Volume (m^3)		1,005,912	948,947	1,051,623	914,711	58,961	596,475	1,110,958	1,091,025	1,023,258	1,117,595	1,041,800	977,551	10,938,816
Overburden Volume (m^3)		224,684	365,117	389,568	229,286	445,904	520,419	413,428	529,821	396,816	322,414	533,194	314,613	4,685,266
Coal tonne (m^3)		1,245,545	1,059,811	1,132,895	780,850	566,142	845,727	1,209,835	1,190,115	1,210,027	1,125,129	1,131,502	1,072,001	12,569,579
Linear Advance (m)		879	829	919	800	52	521	971	954	894	977	911	855	9,562
Blasting detail Interburden														
3m spacing	Pre-split holes (nr.)	293	276	306	267	17	174	324	318	298	326	304	285	3,187
7m burden x 9m spacing	Pattern Holes (nr.)	887	837	927	807	52	526	980	962	902	986	919	862	9,646
Blasting detail Overburden														
5m burden x 5m spacing	Pattern Holes (nr.)	1,634	2,655	2,833	1,668	3,243	3,785	3,007	3,853	2,886	2,345	3,878	2,288	34,075
Blasting detail Coal														
5m burden x 5m spacing	Pattern Holes (nr.)	5,190	4,416	4,720	3,254	2,359	3,524	5,041	4,959	5,042	4,688	4,715	4,467	52,373

As per **Table 7**, the waste loading consists of Dragline blasting (Interburden volumes) at 11 Million m^3 per annum. For the Truck and Shovel pre-strip waste an additional 5 Million m^3 of waste rock (Overburden Hards) needs to be blasted to expose the coal seams. To blast these volumes around 10 000 holes for the Dragline infill, and 34 000 holes for the truck and shovel waste need to be blasted. Pre-split holes for the Interburden amount to just over 3 000 holes, but these hole remain un-stemmed. All the infill pattern holes need to be stemmed in order to reduce fly rock and air blast. The stemming length should consist of a good quality inert material such as crushed aggregate, and should cover a recommended length of at least 20 times the holes diameter (BME, 2007).

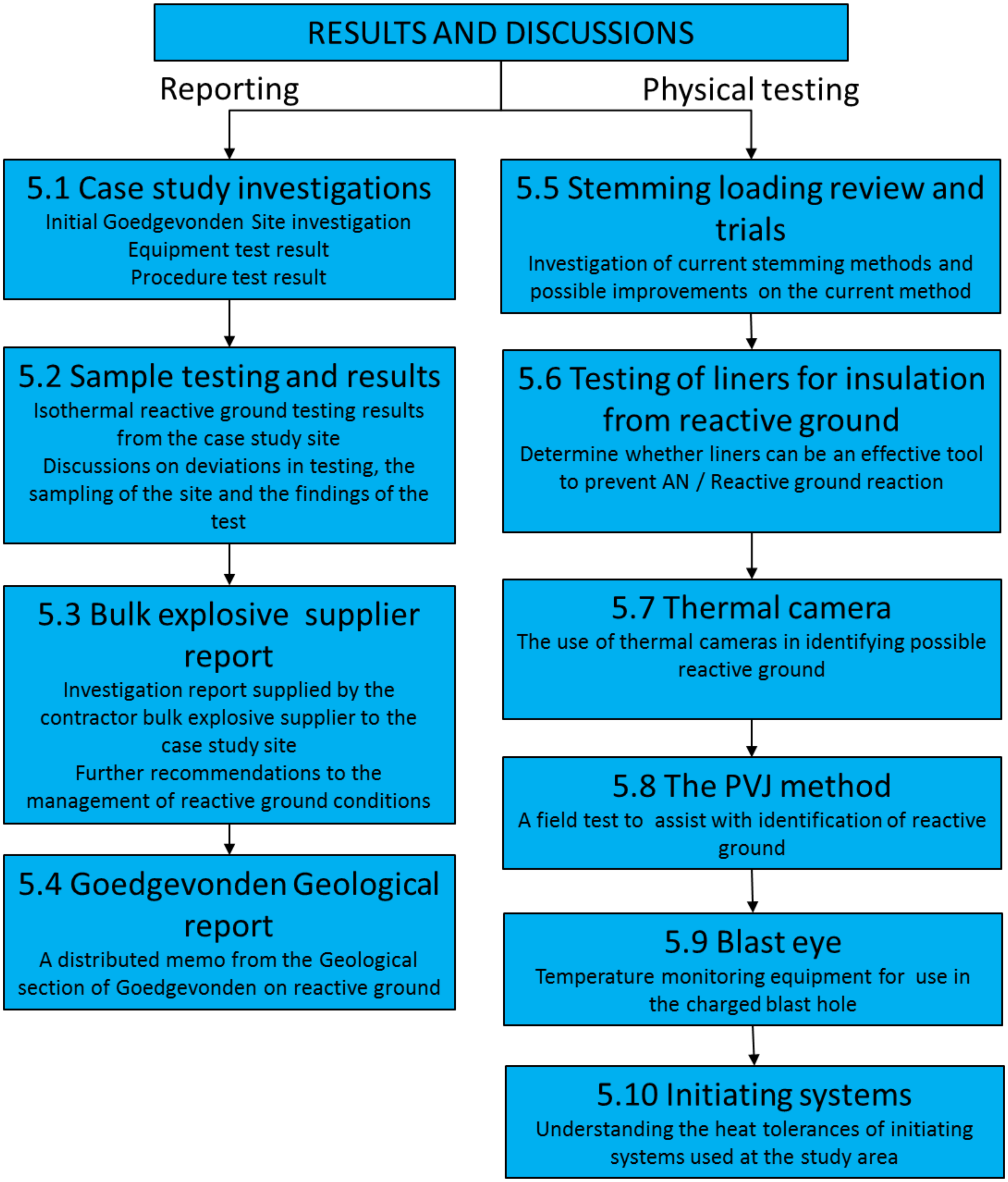
Table 8: Time usage for blasting crew at Goedgevonden Colliery (Produced by Botha, 2013)

Time usage														
Time usage		Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14	Total
total days	**Calender days**	31	28	31	30	31	30	31	31	30	31	30	31	365
Dayshift weekdays only	**Weekend**	9	8	9	8	10	8	8	10	8	9	9	8	104
Public holidays	**Unscheduled days**	1	-	1	3	2	1	-	1	1	-	-	3	13
No work due to bad weather	**Idle days**	3	3	3	2	1					1	2	3	18
Work days available	**Working days**	**18**	**17**	**18**	**17**	**18**	**21**	**23**	**20**	**21**	**21**	**19**	**17**	**230**
9.5 hr / shift	**Shift time (hr)**	171	162	171	162	171	200	219	190	200	200	181	162	2 185
2hr meetings/ line-up/ travelling	**Operational delays (hr)**	36	34	36	34	36	42	46	40	42	42	38	34	460
	Available time (hr)	**135**	**128**	**135**	**128**	**135**	**158**	**173**	**150**	**158**	**158**	**143**	**128**	**1 725**

As indicated in **Table 8**, of the 365 calendar days in a standard year, only 230 days are available as per the standard working agreement for the Goedgevonden blasting crew. Normal working time for the blasting crew as per the labour agreement is standard dayshift for five days of the week. Any other working time will constitute overtime and overtime payment. As seen in **Table 8,** 104 days are lost due to weekends, and a further 13 days are unscheduled because of public holidays. A further 18 days are lost due to idle time. Idle time in this case is based on time lost in the past years due to access being restricted to the mining pit due to bad weather conditions. These weather conditions include excessive dust, rain and mist.

A normal shift will be 9.5hr, with operational delays of 2hr per day for fatigue, travelling and meetings. This leaves a total of 1 725hr per year where focused work on the blast block can take place. Therefore the blast crews need to prepare 9.1Km^3 waste and 7.3Kt coal for blasting every working hour. This is very important when considerations have to be made with the systems and procedures used to complete the preparations of a blast. Any additional work that will be assigned to the blaster when considering the management of reactive ground will need to consider these factors, as it may reduce the risk of a reactive ground incident, but increase other risks due to excessive workload on the blasting crew.

CHAPTER 5 - RESULTS AND DISCUSSIONS



5.1 Case study investigations
Initial Goedgevonden Site investigation
Equipment test result
Procedure test result

5.2 Sample testing and results
Isothermal reactive ground testing results from the case study site
Discussions on deviations in testing, the sampling of the site and the findings of the test

5.3 Bulk explosive supplier report
Investigation report supplied by the contractor bulk explosive supplier to the case study site
Further recommendations to the management of reactive ground conditions

5.4 Goedgevonden Geological report
A distributed memo from the Geological section of Goedgevonden on reactive ground

5.5 Stemming loading review and trials
Investigation of current stemming methods and possible improvements on the current method

5.6 Testing of liners for insulation from reactive ground
Determine whether liners can be an effective tool to prevent AN / Reactive ground reaction

5.7 Thermal camera
The use of thermal cameras in identifying possible reactive ground

5.8 The PVJ method
A field test to assist with identification of reactive ground

5.9 Blast eye
Temperature monitoring equipment for use in the charged blast hole

5.10 Initiating systems
Understanding the heat tolerances of initiating systems used at the study area

5. RESULTS AND DISCUSSIONS

5.1. Case study investigations

5.1.1. Goedgevonden Site investigation

On the 21st of October 2010 five holes self-detonated while a shale burden blast was being prepared. As a result an investigation was initiated to determine the cause of the incident. The investigation indicated that blast holes were primed and pumped with bulk explosives. The blast crew were completing the tie-up of the blast block when 5 holes self-detonated. As illustrated in **Figure 19**, one crew member reported being approximately 50m away from the detonation, and the two other blasting attendants were working at the free face of the blasting area about 150m away from the initiation.

As described in **Section 4.4.1**, the strip width is usually 65m similar to the day of the incident and 280 holes were charged in preparation for the blast. A staggered pattern was drilled at a burden and spacing of 6 meter by 6 meter. The average depth of the shale burden was 4,45m. This burden is usually drilled with a 127mm diameter DM30 drill, but in the case of this blast a 251mm diameter hole was drilled using a Pit-Viper 275 overburden drill. This was done due to breakdown constraints on the DM30 drills. The holes contained around 1m to 2m of water prior to charging as recorded by the blasting crew.

Sasol 30m EZ Dets were used and BME's HEF100 Bulk Explosive pumped at a density of 1.02 completed the charging of the holes. The explosive charge occupied around 2m of the drilled holes. The actual PF of the blast was calculated at 0.47 kg/m^3. The holes were stemmed using waste slag crushed to >25mm diameter. The stemming filled the holes for the remaining 2 to 3 meter of the hole (Goedgevonden. Blast report. OB 0422 0421, 2010).

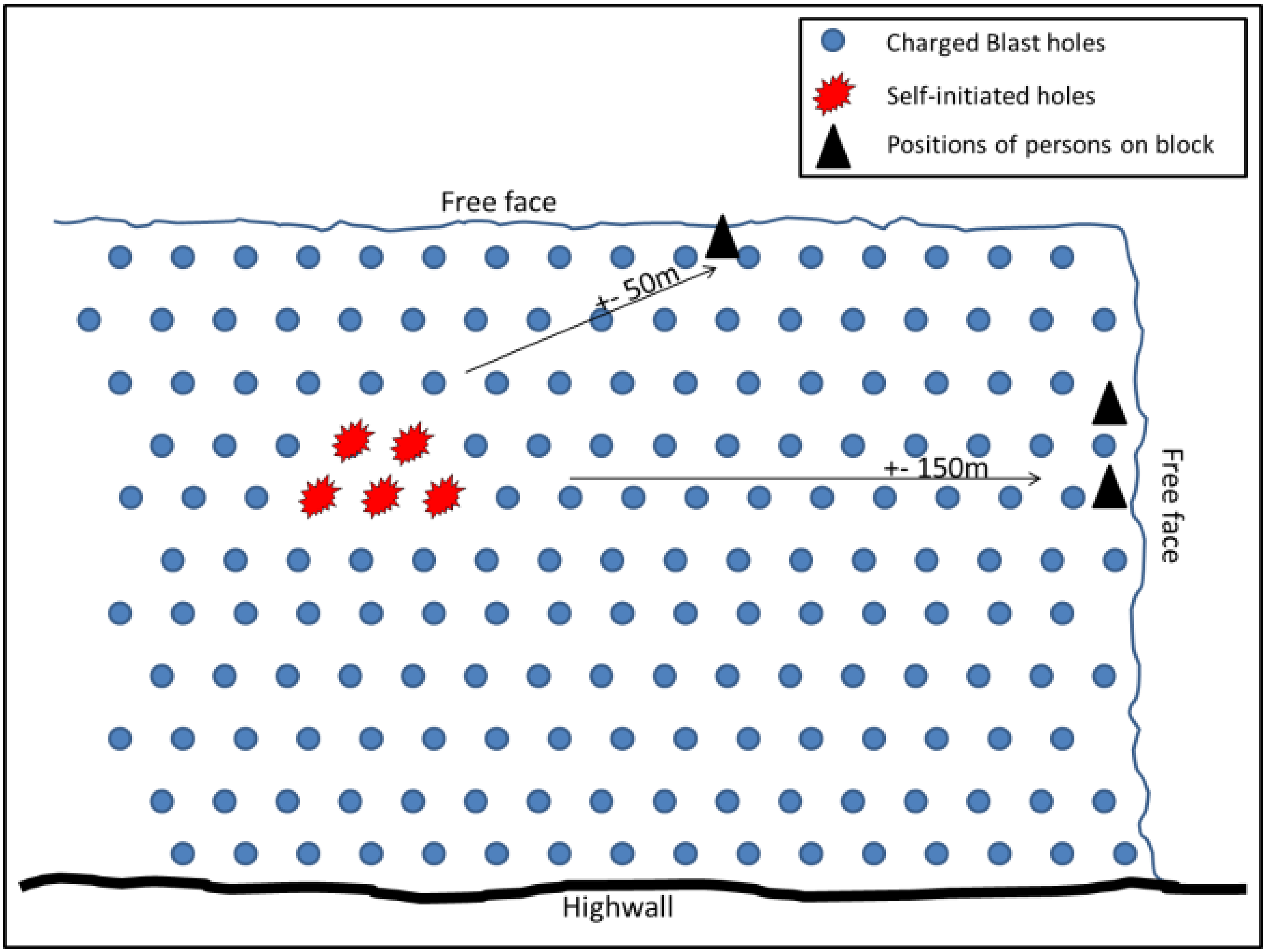


Figure 19: Schematic diagram of the blast (Produced by Botha, 2010)

As can be observed from **Figure 20** and **Figure 21** a white powder like material can be seen throughout the blast block. This is an indication of oxidised sulphides, in this case the sulphide Gypsum (De Korte, 2013).

Figure 20: Photo of blast showing self-initiated area (Photo taken by Stenzel, 2010)

Figure 21: View of self-initiated holes from the unaffected area of the blast block (Photo taken by Stenzel, 2010)

Figure 22 indicates that the explosives did function properly during the follow-up blast, as can be seen by the material properly fragmented as per the blast design. As observed in **Figure 22** no smoke could be seen at the time of the initial blast, however, as the investigation at the site continued smoke became more apparent and temperatures continued to increase until recorded at 380°C twelve days after the incident as per **Figure 23.**

Figure 22: Photo of completed blast of affected area 22 October 2010 (Photo taken by Stenzel, 2010)

Figure 23: Photo of blasted area 12 days after the incident (Photo taken by Stenzel, 2010)

5.1.2. Equipment testing

The following important information was recorded as part of the incident:

- No electrical equipment was used or present on the blast block.
- No other source of ignition was found on the blast block.
- All equipment used to charge the holes were found to be in order.
- All equipment used to stem the holes were found to be in order, however, the crew were very slow in completing the stemming of the holes. The stemming of the holes were done using a small hydraulic shovel, (Skid steer) to tram stemming material from loading points to the blast hole.

5.1.3. Procedure testing

The following were noted:

- No reactive ground procedure was in place for the site.
- Holes drilled in advance of the charging of the holes, but as per drill plan, were completed several days before charging started. Drilling crew were allowed to

drill all available ground and it was common to leave holes for weeks before charging commences as per production requirements. Charged holes were allowed to “sleep over” as stemming of the holes required some time to complete.

5.1.4. Discussion of the preliminary investigation

The preliminary investigation of the incident that was done on site highlighted some interesting points and concerns that can be taken into consideration for the recommendations for the management of reactive ground.

The stemming of the holes led to a long delay in the completion of the blast. This is a major finding and will be discussed further in **Section 5.5**, stemming loading review and trials. It is essential that a method of stemming is introduced that will effectively reduce the time required to fill each hole to the correct stemming depth and if possible be undertaken by the current blasting crew.

Observations on the drilling of holes were made. The drilling capacity outweighs the stripping capacity of the digger fleet, as well as the charging capacity of the Drill and Blast production crew. Therefore, the drills were able to drill far in advance of the loading face. Reference to the time drill holes are left open before being charged and blasted, must be considered during the conclusions, as this activity must be kept to the minimum, i.e. not allowing the reactive surface to increase unduly for excessive periods of time.

The most important thing to note in these findings is the lack of a reactive ground drill and blast procedure. Previously no reactive ground incidents had been positively identified in the area. With no procedure in place to deal with reactive ground, the mining personnel were untrained and therefore unprepared for the possibility of a reactive ground incident on the mine. A formal procedure needed to be put in place to address the shortcomings in the management of possible reactive ground conditions.

The proposed recommendations of this research project will aim to give guidance to such a procedure.

5.2. Sample testing and results

5.2.1. Isothermal reactive ground test results

Sasol Nitro Technical were informed of the incident at Goedgevonden Colliery and requested to assist in the investigation as an unbiased third party. The sampling and testing was done as per the Australian Explosives Industry and Safety Group Inc. (AEISG) (2007) Code of Practice, Elevated Temperature and Reactive Ground. The report stated that some deviations were recorded during the testing of the samples that fell outside of the Code of Practice, but were allowed to pass as it is not expected to affect the results.

Deviations from the Code of Practice:

The milling of the sample was done through a 212 *μm* sieve and not through a 250 *μm* sieve as directed in the Code of Practice. Weathering byproducts preparation was only ferric sulphate, a combination of ferric and ferrous sulphates. An oven was used for the isothermal condition compared to the Code of Practice recommended use of an aluminium block in a dry block heater (AEISG, 2007).

Sampling of the investigated site:

Two sets of samples were taken from the area and sent for analysis. One sample (**SAMPLE 1**) consisted of shale drill chippings near the area (200m away) where the incident took place. The second sample (**SAMPLE 2**) consisted of pieces of shale directly from the detonation area.

Results from the sample testing:

Table 9 indicates the elemental iron and sulphur content of the two samples. Note that Sample 2 indicates very high levels of both iron (Fe) and sulphur (S) as well as an increase in temperature over that of Sample 1, as seen in **Figure 24**.

Table 9: Elemental iron and sulphur content of the samples (Delagey, 2010)

Sample	Fe	S
	(ppm)	(ppm)
Sample 1 (drill chippings near area)	736	0
Sample 2 (detonation area shale)	5700	4151

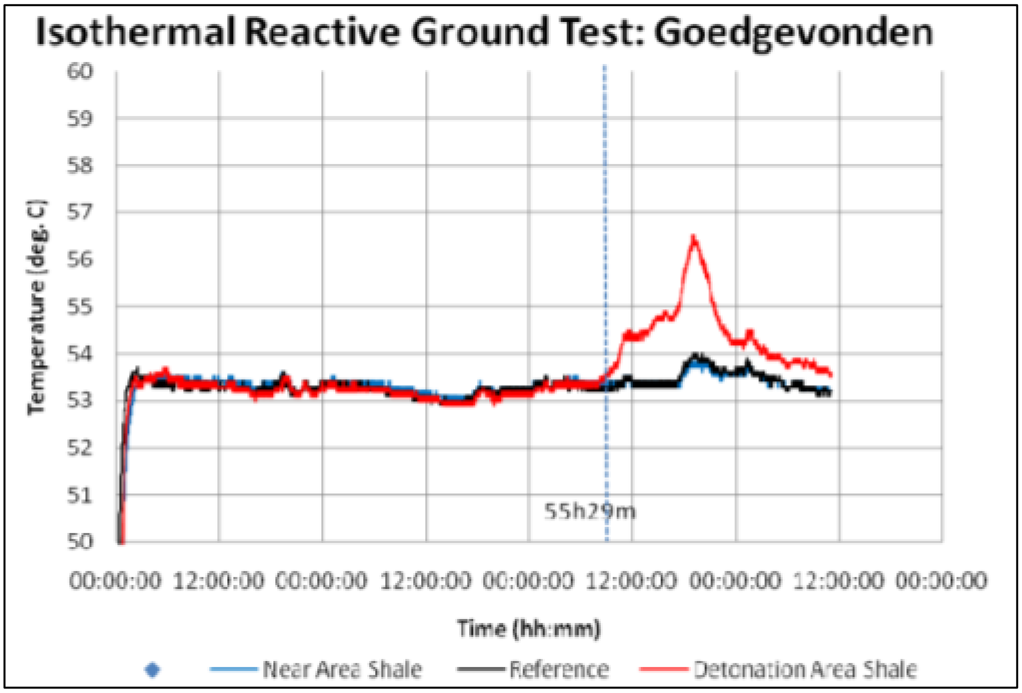


Figure 24: Isothermal environment temperature – time traces for shale mixed with ammonium nitrate (Delagey, 2010)

Findings:

The high iron and sulphide reading found in SAMPLE 2 (Detonation area shale) indicate that iron sulphides are present in the sample. The sample also shows an exotherm in excess of 2°C above the background temperature when ammonium nitrate is placed in contact with the sample. These tests confirm that the shale at the detonation area can be considered reactive (Delagey, 2010).

5.2.2. Discussion of the Isothermal reactive ground test results

The sample testing by a third party laboratory indicates a positive finding or reactive ground found at the Goedgevonden incident site. If testing was done prior to the incident, it may have alerted the production team of the risk and mitigating steps could have been taken. It is concluded that periodic testing throughout the working pit and ahead of the workings is necessary to assist with the prediction of possible reactive ground. The recommendations will address formal sampling and testing for reactive ground. The formal testing regime set out by the mine will generate test results that can assist with determining the maximum allowable sleep time for explosives on site. It is also important to note that the sample some 200m away from the detonation site did not prove reactivity, and therefore the testing for reactivity may need to incorporate a selection regime of far less than the 200m spacing as used in these tests.

5.3. Bulk Explosive supplier report

The bulk explosive supplier to Goedgevonden Colliery was requested to investigate and report on the stability of their product in reactive ground and give recommendations if needed to assist in the management for safe blasting in reactive ground conditions.

A report was submitted by Tony Rorke (2010) explaining the stability of the BME Bulk explosives. It is important to provide confirmation that the bulk explosive is stable and will not detonate at elevated temperatures. This information can then be used to assist in generating the management plan where the use of bulk explosives is concerned.

As shown in Chapter 2, **Section 2.2.4**, Bulk explosive reaction, the tests done by BME in 2004 concluded that their emulsion bulk explosive will not react violently when exposed to temperatures exceeding 300°C. It is not mentioned for what period of time the explosive can be exposed to this temperature, and therefore worst case should be assumed where it will eventually deflagrate, as per the sample reaching 302°C.

All commercial bulk explosives contain ammonium nitrate, thus having the tendency to react with any present sulphides. BME bulk explosive contain a high percentage calcium nitrate in its formulation and is therefore more stable for use in areas of elevated temperatures as it does not degrade over time. Therefore, because of the high percentage of calcium nitrate present in the BME formulation, the reaction will be slower compared to a bulk explosive containing only ammonium nitrate, or lower quantities of calcium nitrate. Even at extremely high temperatures, the emulsion tends to burn and does not react violently. This would then lead to deflagration of a blasthole in extreme case, and not necessarily detonation. The emulsion also contains high percentage water in the formulation that will reduce the sensitivity of the bulk explosives to a level where it will only detonate with a booster as primer for the reaction. The results of the testing done by BME as per **Section 2.2.4**, confirm that HEF100 remains insensitive at elevated temperatures and therefore remains a safe product for use at Goedgevonden Colliery.

A point is made in the report on the sequence of the premature firing of the blastholes. As seen in **Figure 22**, the material around the self-detonated holes shows good fragmentation. Because of this it can be assumed that the holes did detonate properly and that the holes did not deflagrate in a low order detonation as would be the case if the emulsion itself reacted to a point of initiation. The fact that the holes fired in a row strongly suggest that a surface detonator or shocktube that was lying on the surface around the blastholes reacted to heat and detonated.

5.3.1. Recommendations from the Bulk Explosive supplier report (Rorke, 2010)

1. Areas identified as reactive ground should be treated as hot or reactive areas and a procedure regarding the blasting work in such instances, must be applied.
2. Pure emulsion bulk explosives should be used in areas suspected of reactive ground, as it contain the least amount of pure ammonium nitrate.
3. A systematic procedure should be followed to prime the blast block after the holes have been charged up with the bulk explosive, to minimise exposure time of the more sensitive components of the blasting accessories.
4. Only essential personnel must be present close to the charged and primed blast block to minimise exposure to the risk.

5. If excessively elevated temperatures are measured on the surface of the blast block, it is recommended that a layer of inert material of at least 20cm thickness be placed throughout the affected surface. This need to be done to reduce the exposure of the surface initiating system to the reactive ground.
6. Whenever the environmental considerations allow an increase in fly-rock and air-blast, the holes may need to be left un-stemmed. This should be done especially if the stemming of the holes will take up a lot of time. Un-stemmed holes are also less confined. This means that if there is an increase in temperature exceeding 300^oC, any reaction will only result in deflagration and not detonation of the hole.
7. The size of the blast block should be pre-determined to allow the blast to be fired with the minimum delay. Long delays such as reloading of bulk explosive trucks, should be avoided.
8. Temperature monitoring should be done throughout the operation.

5.3.2. Discussion of the Bulk Explosive supplier report and recommendations within the report

With this report it is confirmed that the bulk explosive used on site was within the required parameters for use in reactive ground or elevated temperature areas, as the explosives used can withstand temperature exceeding 300°C. With the test data available it can be concluded that the current bulk explosive is favourable for use on opencast mines where reactive ground may be found. It will be recommended that pure emulsion explosives be used when reactive ground is encountered or suspected.

Again the point is made in the Rorke 2010 report that a procedure should be in place to address the proper steps to be followed when encountering reactive ground on a mine site. As per the recommendations, the mining site must include in the procedure a step by step system to prime, charge and blast the block in order to minimize exposure times to the risk by distributing the work effectively to the essential crew.

The surface area of the blast block will need to be monitored constantly. A thermal scanning device will be required to check the temperatures. If the block still needs to be drilled, and the area allows, a layer of inert material must be placed on the surface of at least 20cm thick. This will assist is removing contact between the surface delays and the hot surface while preparing for the blast.

Stemming of reactive ground blast holes is very crucial. It must be taken into account whether stemming of blastholes is necessary to reduce fly rock and ground vibrations, as well as increasing fragmentation within the blasthole radius. If temperatures of the blast area increase rapidly, the blast should be initiated without delay. If the environmental factors allow, confirmed reactive ground blasts should be initiated without stemming the holes to reduce preparation time. The recommendations in this report will allow for planning of blasts that give options for both stemmed and un-stemmed scenarios.

The planning of the blast must be made in such a way that it can be initiated the same day as the charging start. Details must be available on the size of the block in order to calculate the complete amount of explosive required. Delivery time of the explosives and accessories must be confirmed before the operation commences.

The final recommendation to be taken into account is the monitoring of temperatures. Surface temperatures and in-hole temperature monitoring is critical when working around suspected reactive ground. A continuous monitoring sequence of the pit surface temperatures must be enforced to assist with early detection of risk areas.

5.4. Goedgevonden Geological Report

A memo from the Goedgevonden Colliery Geologist (Ngomezulu, 2011) was issued after the incident to further explain reactive ground conditions and identify the risk areas on site where reactive ground may be expected. The following figures were extracted from the memo:

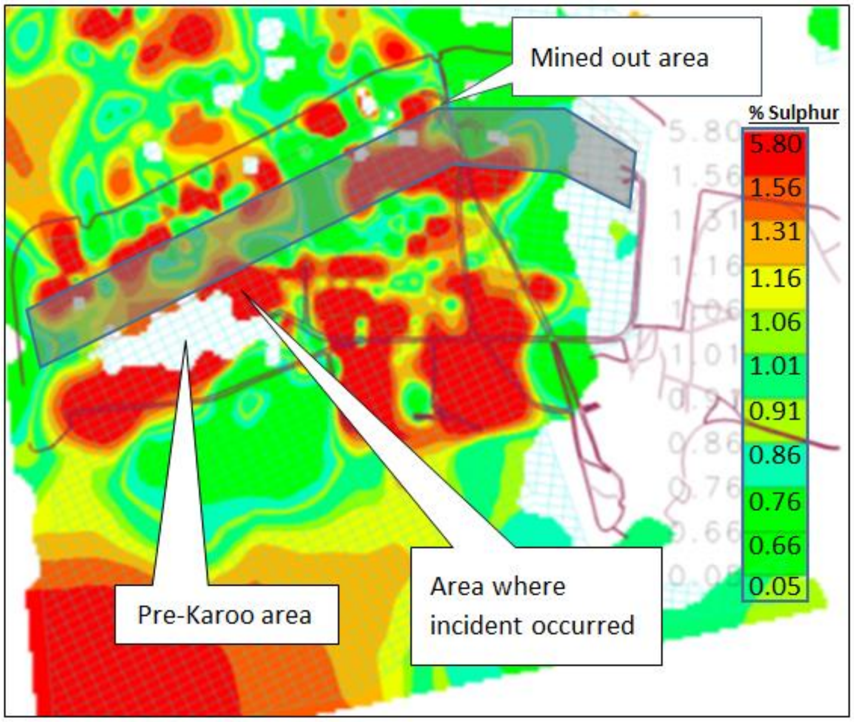


Figure 25: Map of Goedgevonden Colliery indicating the sulphur content of the 4Upper seam (Ngomezulu, 2011)

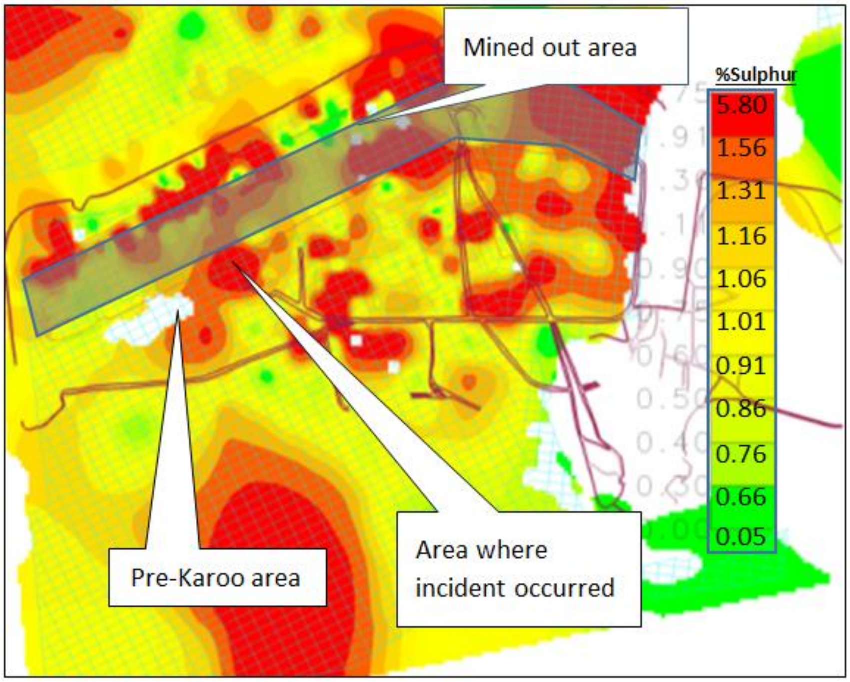


Figure 26: Map of Goedgevonden Colliery indicating the sulphur content of the 2Upper Seam (Ngomezulu, 2011)

As seen in **Figure 25** and **26** there are spots of high sulphur coal throughout the reserve. Red colour indicating higher sulphur compared to a lower sulphur contents of the yellow to green colours. The high concentration of sulphur in the host rock above the coal seam may be the result of a process called metasomatism. During this process hydrothermal fluids can remobilise minerals, like sulphur found in coal, and redistribute into incompetent upper host rock. There it can become concentrated.

The general Pre-Karoo area indicates that significant geological activities took place in the Goedgevonden reserve, allowing the phenomenon called metasomatism to transport the sulphur into the weak shales above the 4 Seam coal.

5.4.1. Discussion of the Goedgevonden Geological Report

It is clear in the above **Figures 25 and 26** that it will be difficult to clearly define danger areas and have separate strategies for different sections of the mine based purely on the sulphur content of the coal seams. Large areas of high sulphur coal have already been mined out with no record of previous incidents. The geological information from the mines geology department can however assist in identifying higher risk areas and more sampling can be concentrated in these areas. It is recommended that the Geology section of the mines Technical team be consulted before drilling, charging and blasting takes place. They will need to examine and indicate whether the section has a possibility of high sulphur content and advise accordingly.

5.5. Stemming loading review and trials

In Chapter 2, **Section 2.2.6**, Methods of controlling self-detonation in reactive ground, specialised stemming material was suggested to assist in the management of the risk. At Goedgevonden the stemming material used in stemming blastholes, is crushed slag aggregate. The material is inert, easy to handle in both wet and dry conditions, and safe for use in the Goedgevonden environment.

However, during the site investigation (refer to **Section 4.2**) a comment was made by the blaster that the stemming of the holes during the incident took a long time to complete. A review of the stemming protocol on Goedgevonden was done. The purpose of the investigation was twofold:

1. Is the current stemming method safe for reactive ground work?
2. Are there possible improvements available for the current method?

5.5.1. Skid Steer loading of stemming

At Goedgevonden Colliery, prior to the reactive ground incident, the accepted means to stem a blasthole involved a small Skid steer rubber tyre loader. Crushed aggregate is delivered next to the blast block in 10 tonne loads. The Skidsteer, manned by an operator and spotter, will then dig and carry the aggregate to the charged blasthole and fill the hole to surface.

Figure 27: Photo of Skid Steer loader used for handling stemming material on a blast block

A cycle time test was done during the blast preparation on an overburden blast (See **Appendix A**) and the results were as follows:

- To fill a 251mm diameter blasthole required an average of 3 loads per hole.
- On average, it required 102 seconds to make one return trip, loading with aggregate from the source, dumping in the blasthole and returning for another load.

- A total of 5 minutes, 6 seconds were required to complete each hole with stemming material.
- A blast block of 280 holes will therefore, without any interruptions, take approximately 23 hour, 47 minutes to complete.
- **Table 8** blasting volumes indicated that the blast crew should be physically present on the blast block for work for around 7.5 hour per day. Therefore, the loader should be able to complete the stemming of a 280 hole blast block in 3.2 days.

In a reactive setting the stemming time required to complete a blast block is dangerously long. Even though the reaction time of reactive ground with ammonium nitrate cannot be predicted with a high degree of accuracy, it can be concluded that “sleeping over” of a blast due to delays in stemming of the blast is an unacceptable risk and should be mitigated as much as possible.

5.5.2. Stemming truck trials

Trials were conducted to assess whether stemming can be delivered to the blast holes by faster means that would allow the blast to be initiated without having to continue stemming the following day. **Figures 28 - 30** indicate the procedure followed when using a stemming truck.

The stemming truck was tested at Goedgevonden Colliery to assess the possibility of delivering a faster load to the blast hole. A wheel loader used for various activities on the mine was used to assist with loading the stemming truck with 15m^3 of aggregate. The stemming truck then needed to travel to the blast block, unload, and return to the loading site approximately 4 km away from the working pit. The truck utilises a small conveyor system than draws the stemming material from the bucket and into a chute, which then feeds into the blast hole. An assistant can help to spot the hole position and assist with feeding issues from the conveyor, but this isn’t a requirement, as the truck mechanisms all run remotely from the driver cabin.

Figure 28: Stemming truck delivering crushed aggregate to the blast block (photograph taken by Botha, 2011)

Figure 29: Stemming truck positioning on the blast block (photograph taken by Botha, 2011)

Figure 30: Stemming truck conveyor delivering stemming material into the blast hole (photograph taken by Botha, 2011)

The cycle time test done (refer to **Appendix B**) on the stemming truck was recorded as follows:

- An average of 25 seconds was taken to fill a 251mm diameter blasthole with 5m stemming material.
- The stemming truck can fill around 15 holes of this size before returning to the aggregate dump site for refill.
- The turnaround time for a refill of aggregate took approximately 25 minutes.
- 280 holes would take less than 2 hours to stem between holes. Add an additional 7.7 hour for loading of the stemming truck, and a total of 9.7 hour is needed to complete a blast block of 280 holes.
- The stemming truck therefore uses around 33% of the time it would take the Skid steer to complete stemming.

5.5.3. Discussion of stemming loading review and trials

The loading of stemming material with the use of a Skid steer can be very time consuming. If the Skid steer or other similar loading technique is used, the size of the blast block must be severely reduced in order to complete the stemming process within the same day of charging. If no faster alternative for the stemming method can be found, the design of the blast should be of such a manner that will allow blasting without stemming the blast holes. The recommended method for stemming reactive ground is a fast delivery system like the stemming truck now in use at the Goedgevonden Complex site.

5.6. Testing of liners (also known as Sleeves) for insulation from reactive ground

In Chapter 2, **Section 2.2.6**, Methods of controlling self-detonation in reactive ground, one of the points investigated to decrease the risk associated with reactive ground, is the possibility of using liners to contain the explosives in the blast holes.

Goedgevonden Colliery was already using liners to contain the explosives in pre-split holes. This assisted with placing the relatively small charge of around 20kg to 40kg at exact locations in the hole. If these or similar liners can be used on the infill blast holes, it may be possible to completely separate the ammonium nitrate based explosives from the surrounding material. The greatest risk associated with this method is the possibility that the liners may tear or split. This will allow the explosive to leak and come into contact with the reactive material, and reaction may take place while the blaster may be of the opinion that the hole is safe and become exposed to unnecessary risk.

5.6.1. Tests on liners conducted at Goedgevonden Colliery

To test this risk, it is necessary to see what would happen if a large amount of explosives is pumped into the liner. An on-site test was conducted to assess the security of liners. Explosives were pumped into liners as per normal pre-split activities. These liners were then extracted from the holes for examination (refer to **Figure 31**).

It can be observed in **Figure 31** that there is minor leakage of the explosive through small tears and bleeding of the explosive as the liner is placed under tension from the loading of explosives. This can prove to be dangerous even though the leakage observed is relatively minor.

Figure 31: Photo of Liner pulled from pre-split hole (Taken by Marton, 2011)

To test the security of the liners when filled with explosive that can be used in the infill holes of a blast, it is necessary to see the possible leakage when completely filled. It is virtually impossible to extract an explosive filled liner from the blast hole. A charged hole can contain hundreds of kilograms of explosives. Liners were filled with explosive and with the assistance of a crane, lifted into the air to simulate the downward pressure of the explosive on the liner (refer to **Figure 32**).

Figure 32: Photo of suspended liners filled with explosives (Taken by Marton, 2011)

Figure 33: Close-up photo of suspended liners filled with explosives (Taken by Marton, 2011)

It is observed if **Figure 32** and **33** that major leakage of the explosive took place when the liners are placed under strain. The bottom of the liner tore and split apart. Throughout the sides of the liner, bleeding of the explosive through the liner is also observed. The test shows that liners will not be an effective and secure way to separate the explosives from surrounding reactive material. It can also be noted the liners took a long time to fill and this was a difficult task to complete without causing spillage.

5.6.2. Discussion of liner tests

The use of liners will not be recommended for use in reactive ground. The product may or may not effectively contain the explosives and will only result in an extremely long and arduous loading process. The physical loading of the liners may also allow excessive spillage around the liner, exposing the surface and sides of the blasthole to reaction. In case of misfires, the product may spill through a ruptured liner into the hole and start a reaction with the reactive ground. The product will take more manpower to handle and expose more people for a longer time to the risk area.

5.7. Thermal Camera

The Geological Section of the Technical Department at Goedgevonden Colliery has a camera that can measure and display temperature. The camera can be utilised to continuously monitor the working pit and increases in temperature can be monitored, recorded and used to assist with the identification of potential risk areas.

5.7.1. Thermal photographs taken and the results obtained

Thermal photos can be taken throughout the mining pit and the images stored for comparison. Each week the routine is repeated and the images compared to the previous week's photos. **Figure 34** shows a photo of an exposed shale area above the 4 Seam close to the western perimeter of the current mining pit. The surface temperature registered 37.8°C.

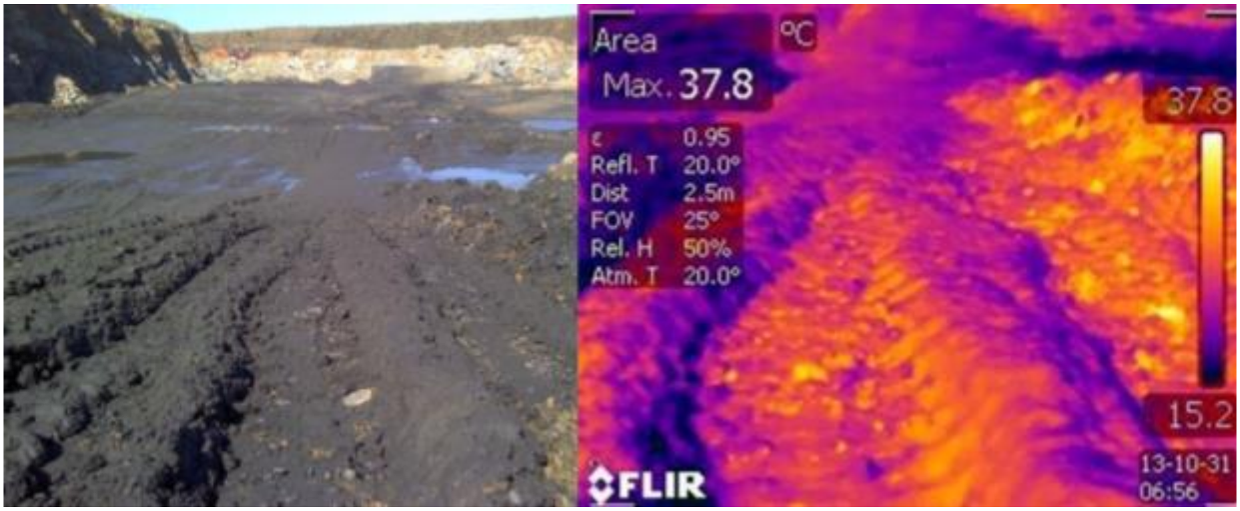


Figure 34: Thermal image of identified risk area at Goedgevonden, 31 October 2013 (photograph taken by Botha, 2013)

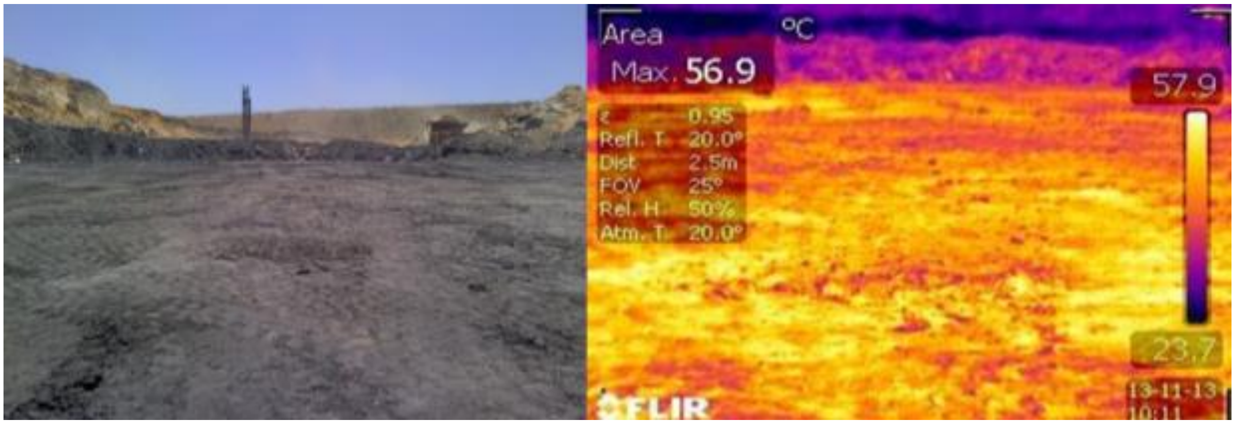


Figure 35: Thermal image of identified risk area at Goedgevonden, 13 November 2013 (photograph taken by Botha, 2013)

The use of the thermal camera is not a clear definition tool to identify reactive ground, but increases in temperature can very easily be monitored and, therefore, it is extremely effective in identifying risk areas constantly throughout the operations.

5.7.2. Discussion of thermal photographs and the associated findings

The camera can be utilised on a drilled block and constantly check the temperatures before any explosive is loaded into the drilled hole. It is a very effective monitoring and logging tool and the thermal monitoring of the working pit can be done to warn of potential risk areas throughout the pit. It will assist in fencing potential risk areas and increase awareness when approaching these areas. The camera can also be used to monitor the temperature of the test cup samples, as discussed in the following **Section 5.8**, The PVJ Method.

5.8. The Pieter van Jaarsveld (PVJ) Method

It is crucial to understand the level of risk the blasting team is exposed to at all times. The most effective way of testing for reactivity is testing in a laboratory. The problem with this testing method is time. The testing process is very slow and time consuming. With no laboratory on site, it is necessary to send the samples away for testing. This process can take several days and even weeks before positive results can be reported. High level confidence geological sampling is necessary to understand the reserve and keep the operations informed of the risk going forward. But a short term sampling and testing technique could greatly improve the day to day risk management of working with reactive ground.

During the 2013 BME conference held in Pretoria, South Africa, a presentation was given entitled: *Dealing with reactive ground.* The presentation and research paper was by Van Jaarsveld and Van Greunen (2013).

In this research paper, a method of sampling and testing for reactive ground was presented that may greatly assist and simplify the testing for reactive ground. The PVJ method was explained and described by Van Jaarsveld and Van Greunen (2013) as follows:

5.8.1. Sampling for reactive ground according to the PVJ method

The sample in this case is made up from drill chippings around the hole. For the PVJ method, 25% of the holes on the blast block need to be sampled, as indicated in **Figure 36**. The area worked in was highly reactive and a large sample area identified to increase the chances of a positive test result in the case of reactivity.

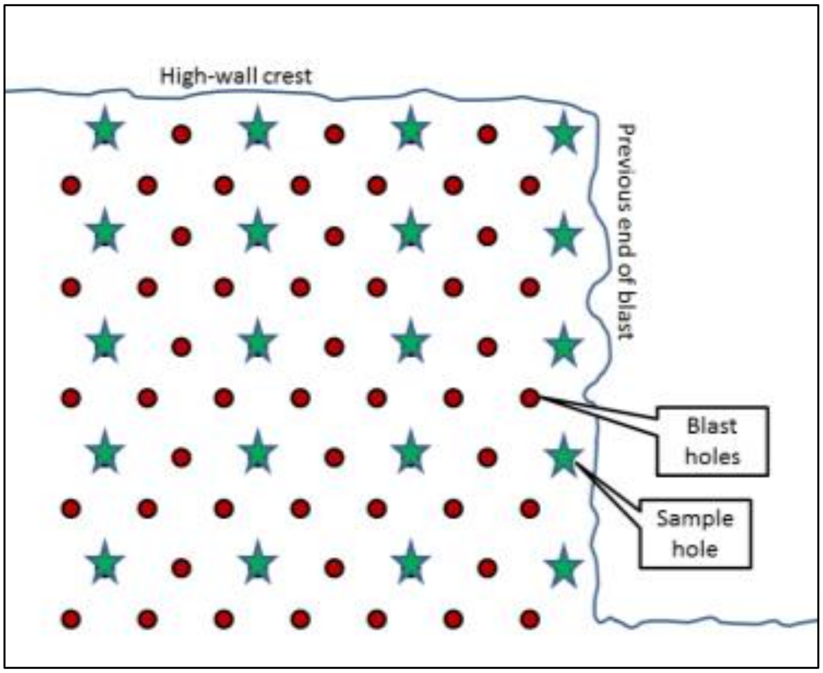


Figure 36: Schematic of blastholes indicating the sampling grid for the PVJ method (taken from Van Jaarsveld and Van Greunen, 2013)

The sample need to be taken from a fresh face exposed in the drill cutting pile. If reactive pyrites can be identified, it should be targeted in the sampling. By focusing on the reactive prone material, the worst case test will prove more visually revealing and identifiable. If the sample is too diluted with inert material, it can give negative results and expose the team to risk.

Figures 37 and **38** indicate the samples taken as part of the testing done at Goedgevonden Colliery according to the PVJ Method.

Figure 37: Cups filled with 250g explosive product for reactive testing (photograph taken by Botha, 2013)

Figure 38: Test cup mix with drill chippings and emulsion explosives (photograph taken by Botha, 2013)

Requirements for the test (refer **Figure 37** and **Figure 38**):

- Thin disposable plastic cups
- 250g drill chipping sample
- 250g emulsion explosive

The chippings sample and emulsion sample need to be mixed together and left in the cup to stand for approximately 8hr. During this period the sample can be visually inspected for signs of reactivity.

When inspecting the cup for reactivity, the following should be inspected:

- Burn holes may appear on the sides of the cup.
- Bleed holes can appear on the surface of the mixture.
- The sample can be measured for an increase in temperature.
- The sample may produce gas.

If any of these signs are found to be positive in the sample, all the surrounding holes should also be sampled and tested. Even though these tests can assist in identifying reactive ground, it should not be assumed that no reactivity is present if the tests prove negative, as the represented sample may not be the worst case sample from the current sampled area.

5.8.2. Discussion and testing

The PVJ test is recommended for use when dealing with reactive ground. It is very easy to follow and gives a good indication of risk with regards to reactivity of the block. The PVJ sampling can be an excellent method to compliment other monitoring devices that can be used throughout the blast block where reactive ground is suspected. The PVJ sampling is nearly cost free and can offset the placing of other monitoring devices throughout the blast block. A staggered test pattern could be recommended as per the recommendations from the researchers study paper; however, it could be offset with other monitoring devices as shown in **Figure 39**. This will assist in reducing the cost of the monitoring devices, as well as having a second optional tool that can assist in the detection of reactive ground throughout the suspected area.

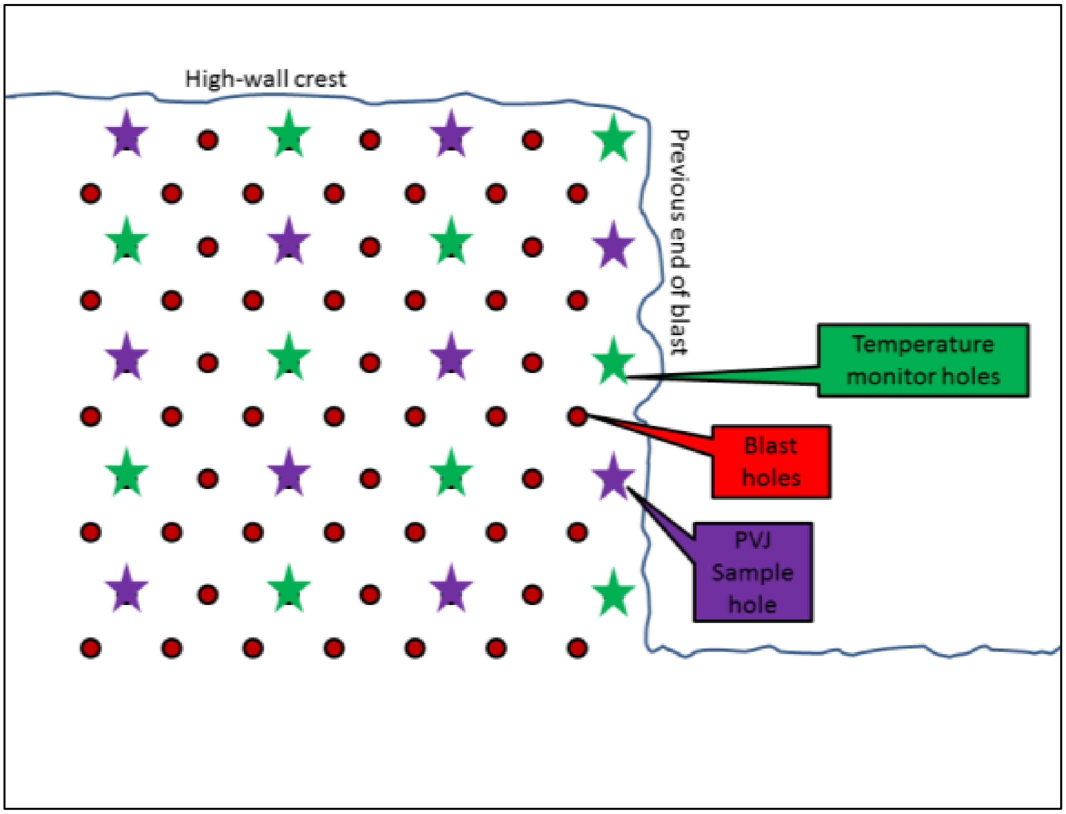


Figure 39: Suggested PVJ sampling staggered with Temperature monitoring probes throughout a blast block

5.9. Blast eye hot hole monitor

The highest risk during the reactive ground charging and blasting operation, is the exposure of the explosives in the blast hole. The explosive is exposed to the reactive environment and is in containment where the heat of the reaction can build up very quickly. Even if the primer is only inserted into the hole at the very end of the loading process, the blaster may not know the exact danger a blast hole may pose. AEL Mining Services introduced a product that is able to significantly reduce the risk of working on a potential reactive ground blasting block. The AEL “Blast eye monitor” was introduced in a presentation from AEL, as part of their customer service agreement to assist their customers with technical support during the incident investigation. Mr B. Swanepoel from AEL Mining Services gave the presentation on *Managing explosives and burning coal (2012)*.

5.9.1. Operation of the Blast eye

The “Blast eye” is a disposable device that is attached to the booster before being lowered into the hole (Refer to **Figure 40**). A probe from the unit is attached to the booster and is lowered into the blast hole, as seen in **Figure 41**. The probe is connected to the red blast eye casing by a 30m connection wire. The blast eye is activated by removing a small tab and a green LED light will indicate an operational device. The Blast eye unit is then planted next to the hole in the drill chippings for stability, with the unit still visible to the blasting crew working in the vicinity. The blaster will be able to have some confidence in the unit, as the red and green LED lights will flash continuously with the unit alarm emitting a sound continuously, if a fault within the unit occurs.

If the temperature of the probe reaches 60°C, a pulsing alarm will sound and a flashing red LED will be visible. If the temperature of the probe exceeds 80°C, the alarm will be delivered continuously and the red LED light will stay on. The unit remain on the blast block with a battery life guaranteed for approximately 8hr usage. The entire unit is then destroyed with the blast.

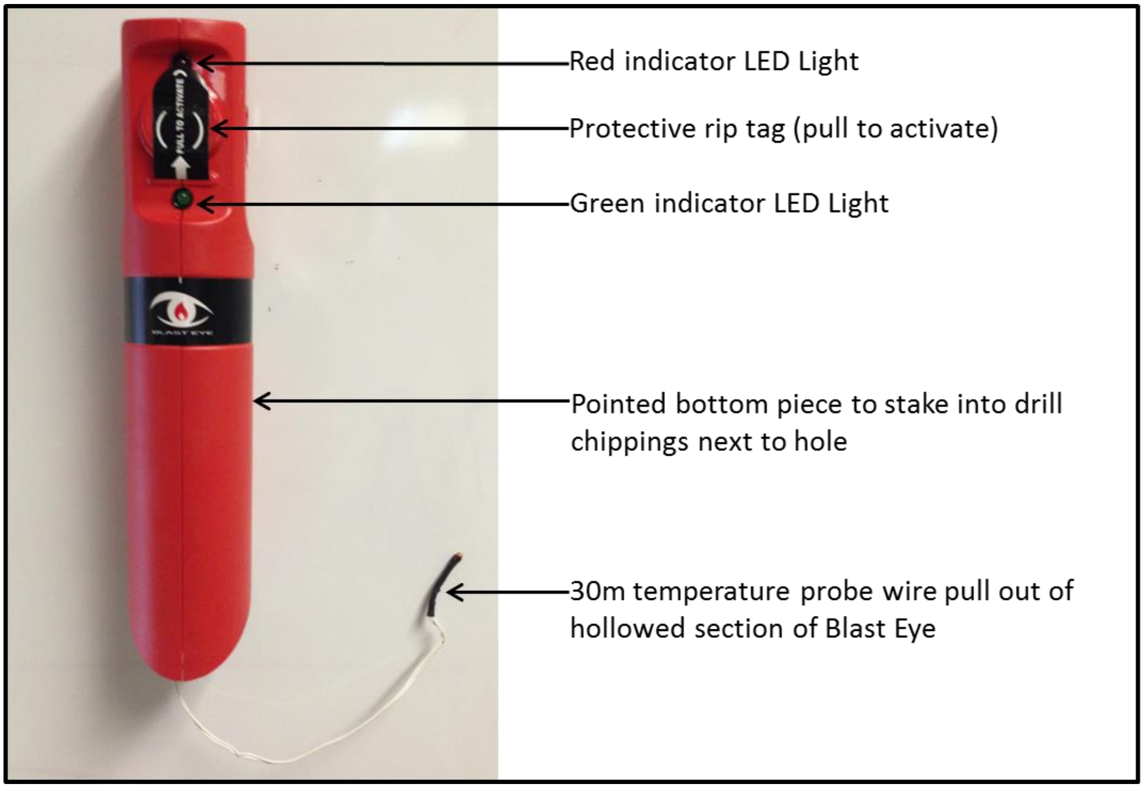


Figure 40: The AEL “Blast eye” monitor (Picture taken by Botha, 2013)

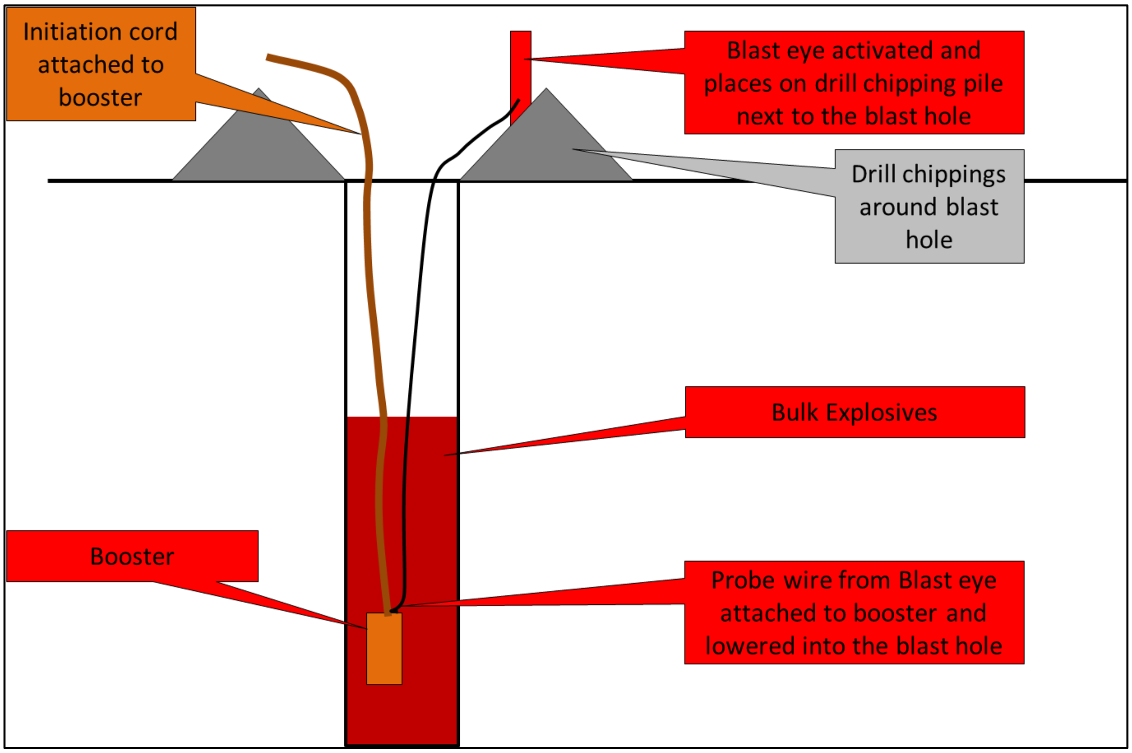


Figure 41: The placement of the Blast eye monitor at the blast hole (Produced by Botha, 2013)

5.9.2. Discussion of the usage of the blast eye

The blast eye hot hole monitor is a key control for loading explosives in reactive ground conditions. It can be recommended as a critical monitoring tool and must be implemented in the management process to ensure the safety of personnel when loading explosives into suspected reactive ground conditions. These units can supplement other monitoring devices on the blast block and should be placed throughout the pattern of a confirmed or suspected reactive ground site. **Figure 41** indicates the suggested use of the monitor throughout the blast block, as the “blast eye” can alternate the sampling pattern on the blast block.

5.10. Initiating systems

To understand the temperature tolerances of the explosives used on the block, an understanding is required of the most common current initiating systems used on the Goedgevonden site. AEL mining services is the current supplier of all the initiating systems required by the site. Discussions were held with their Technical Service Department with regards to the specifications of the products supplied. Various data sheets were supplied presenting the information for this study.

5.10.1. Specifications of the current supplied products used at Goedgevonden Colliery

<u>Shock tube</u>

The Shock tube – Multi SPD, is the product supplied to Goedgevonden Colliery. The specifications of interest when keeping reactive ground in mind is taken from the Technical data sheet (AEL Mining Services, 2013) as follows:

- The product consists of a plastic yellow tubing that is attached to a short period in-hole delay detonator.
- It has two primary short period delays, and is available in various delay timing and length combinations.

- The yellow coloured shock tube has a 18kg minimum break load, is water resistant, as well as resistant to hot and cold temperatures.
- **If the product is exposed of temperatures in excess of 90°C, a spontaneous explosion can occur.**

Boosters

Pentolite boosters are high energy explosives used to propagate the explosion of the shock tube detonators or detonating cord, and further amplify the detonation output to reliably fire the bulk explosive. The booster is made of a plastic cylinder filled with a solid explosive called Pentolite. Pentolite consist of Pentaerythritol Tetranitrate (PETN) and Trinitrotoluene (TNT). The boosters are available in various ranges of Pentolite mass, from 60g to 400g.

The technical data sheet for the Pentolite booster, (AEL Mining services, 2013) describe the relevant information with regards to the booster as follows:

- It is relatively insensitive to detonation by accidental impact, exposure to heat and electrostatic discharge.
- It is completely waterproof.
- **Exposure to temperatures above 80°C will lead to melting of the Pentolite formulation.**
- **In the case of exposure to temperature in excess of 90°C for prolonged periods of time, the booster may prematurely detonate.**

Detonating Cord

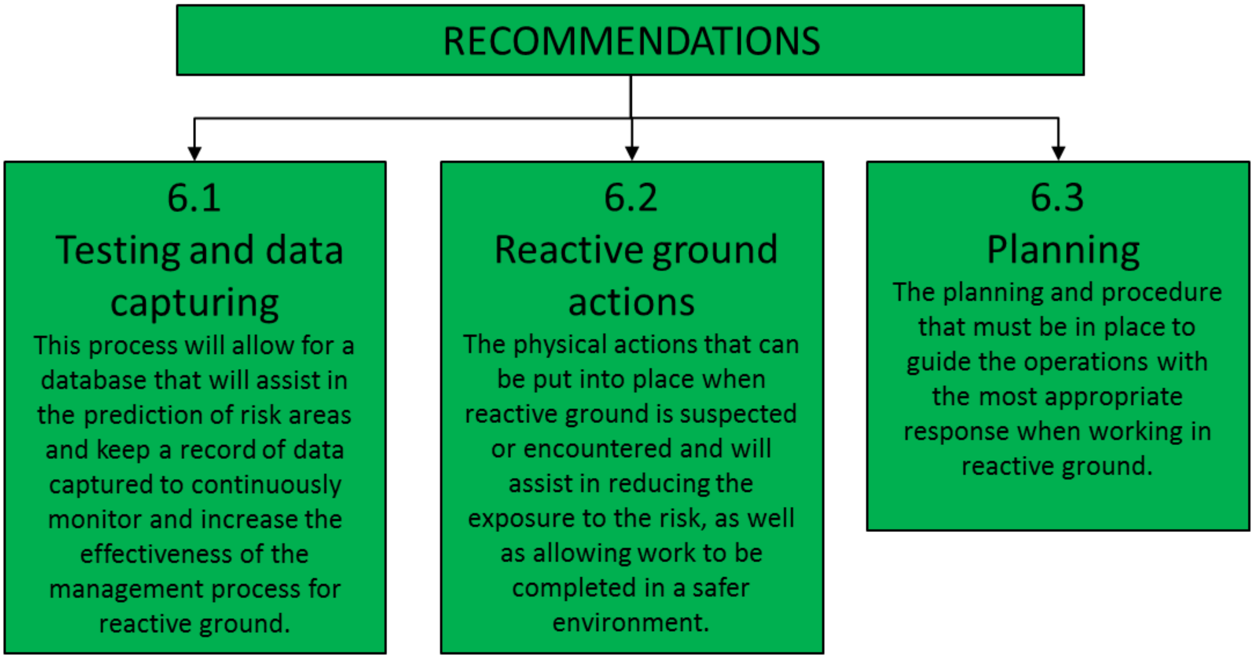
Detonating cord is also used frequently on the Goedgevonden site and the product information from the AEL Mining services, Detonating cord Technical Data Sheet – Revision 2 – October 2011, was studied to understand the limitations of the product specifically with regards to reactive ground. The Powercord® product supplied by AEL Mining Services, consist of a Pentaerythritol Tetranitrate (PETN) column that is encased in layers of tape and yarn, and finally encased in an outer flexible plastic casing. The product is available in various core loads from 5.5g PETN per meter, up to 10.5g PETN per meter, depending on the application. The relevant points concerning the Powercord® product is listed as follows:

- The Powercord® is relatively insensitive to detonation by heat, electrostatic discharge, or other forms of exposure to electricity.
- It has excellent resistance to water and oil.
- **The Powercord® should not be left in an environment where temperatures exceed 90°C as it could result in spontaneous explosion.**

5.10.2. Discussion of the initiating system used at Goedgevonden Colliery

As seen in the descriptions above, these products are extremely vulnerable to temperatures exceeding 90°C. It is therefore clear that the most temperature sensitive equipment on the blast block, will be the initiating systems. When measuring and monitoring temperatures on the blast block, the 90°C maximum tolerance of the initiating systems should be the primary consideration when deciding to clear a blast block due to a rise in temperature. The measuring of surface temperature, as well as the PVJ test sample cups, should use a limit of 80°C, as per the AEL Blast eye monitor, which will allow some safety factor to complete the block as is, and blast the affected area as quickly as possible.

CHAPTER 6 - RECOMMENDATIONS



RECOMMENDATIONS

6.1 Testing and data capturing

This process will allow for a database that will assist in the prediction of risk areas and keep a record of data captured to continuously monitor and increase the effectiveness of the management process for reactive ground.

6.2 Reactive ground actions

The physical actions that can be put into place when reactive ground is suspected or encountered and will assist in reducing the exposure to the risk, as well as allowing work to be completed in a safer environment.

6.3 Planning

The planning and procedure that must be in place to guide the operations with the most appropriate response when working in reactive ground.

6. RECOMMENDATIONS FOR THE MANAGEMENT OF REACTIVE GROUND

The aim of this study is to effectively and safely manage reactive ground conditions in the Witbank Coalfield environment. The recommendations in this study should provide guidance to the operations in minimising the risk the operations and personnel will be exposed to when working with potential reactive ground. It should only be used in addition to already existing drilling and blasting procedures, to assist in making the mining pit safer when working in and around reactive ground conditions.

Distinguish between reactive ground and spontaneous combustion

As seen in Chapter 1 of this research paper, reactive ground incidents have been recorded all over the world. It is clearly a very dangerous and largely unpredictable phenomenon that has surfaced locally in the Witbank Coalfields area. The Witbank Coalfield has been plagued by spontaneous combustion incidents and the major mining houses even sponsored research regarding spontaneous combustion, like the report from the Coaltech Research Association, *Prevention and Control of Spontaneous Combustion*, published by Phillips, H. Uludag, S & Chabedi K, in 2010. Comparatively little research is published regarding reactive ground and due to the nature of phenomenon it can be occurring quite randomly around sites in the Witbank Coalfields area without the site being prepared to deal with the possible catastrophic results it can cause.

Spontaneous combustion occurs when coal is exposed to oxygen and oxidation can occur. If the heat cannot dissipate into the atmosphere, the coal will continue to increase in temperature until ignition occurs and the material will burn.

Reactive ground is ground that contain high concentrations of sulphides that, when exposed to ammonium nitrate, has the potential to react and this reaction generates heat. The temperatures can increase very quickly and can cause a blasthole containing ammonium nitrate explosives to deflagrate or even detonate.

This section attempts to present the information gathered in this paper in steps that should allow an opencast coal mining operation to better understand and manage the risk of reactive ground on their site.

The management of reactive ground

As seen in the above chapters, there is no single tool to completely identify, and control reactive ground when it occurs in opencast coal mines. An integrated risk management approach should be considered to allow as many options possible to detect the risk and reduce the exposure as much as possible. Each site will be able to customise all recommendations to best suit their site.

A team must be formed to formulate the plans and give inputs to mitigate the hazards that will be encountered when dealing with reactive ground. The ideal team should consist of:

- Senior management;
- Technical services including the Blasting Engineer and Geologist;
- Relevant production supervisors;
- Regulatory authority personnel;
- Explosive suppliers; and
- Other affected parties.

Once a preliminary risk assessment is carried out by the team, the management program can be drafted and implemented on site. The sign-off for the procedure must be enforced and be made available to every person involved throughout the process.

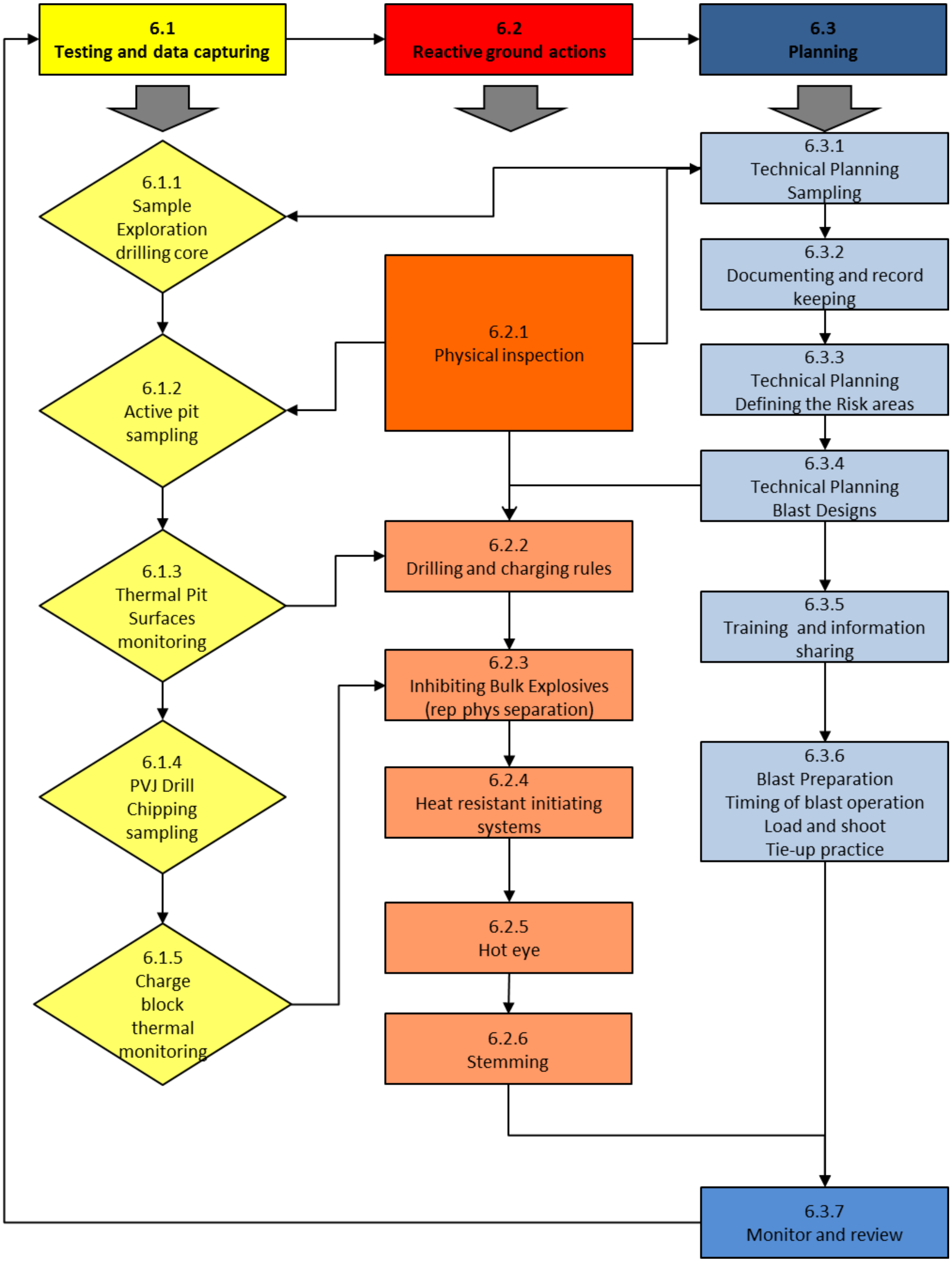


Figure 42: Recommended flow diagram for reactive ground (Produced by Botha, 2013)

As seen in **Figure 42**, the management of reactive ground need to be covered in three main branches that will allow specific actions to flow into a process that could reduce the risk of reactive ground effectively.

The first branch is the testing and capturing of the data. This process will allow for a database that will assist in the prediction of risk areas and keep a record of data captured to continuously monitor and increase the effectiveness of the management process for reactive ground.

The second branch is the physical actions that can be put into place when reactive ground is suspected or encountered and will assist in reducing the exposure to the risk, as well as allowing work to be completed in a safer environment.

The third branch of the process includes the planning and procedure that must be in place to guide the operations with the most appropriate response when working in reactive ground.

The branches involve in the effective management of reactive ground will be discussed further and broken into the specific steps as highlighted in this study.

6.1. Testing and data capturing

It is concluded that the most important factor when dealing with reactive ground is time. Once exposed to ammonium nitrate the reaction will continue to exponentially increase the temperature in the reaction. The earlier one can determine the presence of reactive ground, the earlier measures can be put in place to mitigate the exposure time to the potential risk.

Laboratory testing for reactivity is the most effective way to determine reactivity. Chemical compatibility testing is a reliable way of testing the reactivity of a host rock bearing iron sulphides. Some explosive suppliers have access to laboratories that can do direct compatibility tests between the host rock and ammonium nitrate, and can supply these results to the mining company as part of their service level agreements. Laboratory testing using differential thermal analysis can also be done to determine compatibility.

General Sampling recommendations

Samples should be taken as per the recommendations below (Statpac, 2013). The Geologist on site should be highly involved in the identification of the worst case samples throughout the testing area. This will involve collecting of samples within the shale, identifiable massive sulphide units as well as coal that has a high combustibility index. Samples also need to include rock that is high in iron sulphide or that is pyritic in nature. The following points form part of a suggested sampling procedure:

- A number of samples (2-10) should be taken at every testing site, depending on the variation of sample material exposed on the site.
- The exact location and all data surrounding the sample must be surveyed and well documented. The notes will form part of a locality map and database that will assist in identifying, predicting and defining reactive ground risk areas.
- Core drilling will provide the purest sample for testing and the most accurate finding can be drawn from those samples. It is very important that the core sample must be fresh, as exposure to the elements may influence the test results.
- Picking a sample from a freshly exposed surface is advisable for ensuring a good quality sample, and is recommended when doing active pit sampling.
- Picked samples are preferable, because the larger pieces are less sensitive to oxidation. Great care should be taken when drill cuttings are used for the sample, as it may misrepresent the worst case sample due to dilution and excessive oxidation and affect the findings of the test. If the chippings are not tested on the blast block and have to be moved, the sample must be vacuum sealed and covered.

- The sampler should take the utmost care not to drop the sample, or transport it in any such way that may cause dilution of the sample and misrepresent the test.
- The samples must be clearly marked or labelled with markings that will not rub off or fall off and ensure that the sample can be traced back to the location it was taken from.
- The ideal sample size for testing will range from 500g up to 1kg. It is essential that enough samples are collected for the test, as well as being small enough to handle easily.
- The timing of the sampling should be coordinated with the test laboratory to ensure that the samples get analysed with a minimum amount of delay, ensuring the most accurate findings, as well as giving the site maximum time to react to the results.
- Depending on the exposure rate of the mining site, or the drilling rate of the core drilling, a periodical sampling regime must be determined to cover the pit and continuously test newly exposed areas.
- If the test results show a negative result, on-going sampling can be scheduled to double-up on suspected areas, and spread out into new areas.
- If physical evidence is found that can indicate reactivity, the area must be included into the immediate sampling rotation to test for reactivity.

6.1.1. Sample exploration core drilling

Exploration drilling advances far ahead of the working pit. For purposes of testing for reactive ground, the results will be available long before active mining take place in the area. The core recovered from the drilled hole is undiluted by surrounding material and sample sections can be clearly defined.

The AEISG *Code of Practice for Elevated Temperature and Reactive Ground* (2007) also suggest that the geologist should inspect the core and base their sample selections on the following points:

- Fine to large grain pyrites.
- Black sulphide bearing sediments.
- Sulphides within mineralised rock.
- White or yellow salt on the rock, indicating oxidation.

6.1.2. Active pit sampling

As the mining operation exposes rock to the atmosphere, a rotational sampling regime must be put in place to systematically sample the rock above the coal seams before it is subjected to the drilling operations. The responsible person under supervision from the mine's Geologist will sample and observe the mineralisation of the overburden rock and coal seams and should also concentrate their sampling when the following is observed:

- Fine to large grain pyrites.
- Black sulphide bearing sediments.
- Sulphides within mineralised rock.
- White or yellow salt on the rock, indicating oxidation.
- Yellow/red run-off water indicating acidic conditions from oxidation.
- Spontaneous combustion of overburden waste rock or coal when exposed to air.
- Smell of sulphur dioxide caused by oxidation of the sulphides.
- Significant corrosion on metal tools and equipment in the area.

6.1.3. Thermal pit surfaces monitoring

A routine thermal image monitoring program should be implemented that regularly scan the entire working pit for increases in temperature. A controlled documentation system with records of monitoring points will help to indicate when certain areas are becoming increasingly hot compared to the surroundings. These areas can be flagged and defined as possible hotspots where drilling and blasting operations should assume an increase in risk and deal with the area as per the reactive ground procedure. The distribution of the thermal records, especially if an increase in temperature is detected, is of great value to sensitize the operational personnel to the potential risk.

6.1.4. PVJ drill chipping sampling

When reactive ground is suspected, it is necessary to understand what is happening in the blast hole when the bulk explosive is loaded. The PVJ sampling should be done to complement in-hole temperature monitoring. There is no significant cost involved in the test and can be staggered in between the holes being monitored by the temperature monitoring devices.

The sampling method should be done as described in **Section 5.8**, The PVJ Method. The sampling needs to be done when the first bulk explosive truck arrives on the block, and samples should be placed at the sample hole throughout the pattern.

The samples should be checked for physical signs of reaction, and it is recommended that the thermal camera also be used during its scan of the blast block, to check the sample cup temperatures.

If the temperatures increase above 60^{o}C, or if the physical inspection confirms reaction in a blast hole, the blaster must immediately evacuate, complete the tie-up and fire the blast.

6.1.5. Charge block thermal monitoring

If reactive ground is suspected and the blasting crew is preparing the block to fire, it is recommended that periodical monitoring with the thermal camera or monitoring device be done. The camera can immediately report surface temperatures increases. The thermal camera can, as stated in **Section 5.7**, be used to monitor the increase in temperature in the PVJ samples throughout the blast block.

Any temperatures above 60°C must be reported immediately to allow the blaster to complete the blast block as quickly as possible.

6.2. Reactive ground actions

6.2.1. Physical inspection

Before the work on a block commence a review of the reactive ground database and mine plan must be done. This will assist in having the knowledge of whether the work is advancing into a known risk area or not.

The following factors can be considered when identifying reactive ground (see Chapter 2, **Section 2.2.3**):

- The presence of moisture will assist the oxidation process.
- An acidic environment may speed up the reaction rate. Note excessive rust on metal surfaces.
- Note the particle size of the rock within the environment. Fine dust being the most reactive, broken rock less reactive and solid in-situ material being the least affected by reactivity.

The responsible blaster will need to continuously observe the blast block being prepared for blasting for any signs of heating. These physical signs can be observed:

- Smoke rising from the charged blast holes.
- Smell of fumes in and around the blast holes.
- Bubbling of water or product in the blast holes.
- When listening near a blasthole, bubbling noises may be heard indicating heat in the blast hole.

If any of the blasting crew suspects reactive ground, or hot ground conditions, the blaster must be notified.

6.2.2. Drilling and Charging Rules

The following drilling and blasting rules should be considered:

Drilling:

- If an area is identified with a risk of potential reactive ground, drilling should only be done far enough in advance to allow for single day's charge and blast.
  The holes should not be allowed to sleep over for prolonged periods of time.
- The blast size should be planned prior to the drilling operation to take into account the drill capacity as well as the charging capacity.
- The drilling should be squared off to ensure that no holes remain after the blast is completed.
- If excessive temperatures are recorded on the surface of the blast prior to drilling, a layer of inert overburden material (such as the pre-strip soft soils) should be layered over the surface of the intended blast block to a depth of at least 20cm. This will reduce exposure of the initiating systems to the reactive hot surface.

Blasting:

- With regards to blasting, only holes that can be blasted the same day, should be charged with explosives. The blaster must make sure that the plan received with the charging and blasting instruction for the blast block, is designed for reactive ground, and this must be specifically indicated as such on the plan.
- A systematic procedure must be followed to prime the holes with the initiating accessories after the block is charged with bulk explosive. The loading should start from the point of initiation; this will allow the blaster to tie-up the blast quickly and fire whenever the conditions change. The risk of sleepover exists if the blast cannot be completed timeously.
- Product spillage on the block must be avoided as far as possible, as it can interact with the reactive surface and surface initiation lines. This awareness must form part of the explosive supplier training on reactive ground.
- The procedure must be well known by the blasting crew and set up in such a way as to optimise the available personnel as well as keeping the required personnel to a minimum.

- Temperature monitors must be placed in selected predetermined holes throughout the blast block.

6.2.3. Inhibited bulk explosives

The bulk explosive used on the mining site should not react violently to temperatures as high as 300°C. The explosive supplier should supply proof of testing the product.

When confirmed reactive ground is being approached, all effort should be made to only use a form of inhibited explosive. The inhibitor in the explosive will lengthen the reaction time between the sulphides and the ammonium nitrate and will allow time to complete the charging and blasting of a reactive ground blast. The explosive used should be prioritised as follow:

Low Risk: Use pure emulsion bulk explosive due to its relative low ammonium nitrate content compared to bulk explosives containing ammonium nitrate prills. One such form of semi-inhibited bulk explosive, is the emulsion explosive currently supplied by BME. It contains a high percentage calcium nitrate, substituting some of the reactive ammonium nitrate, and therefore creating a less reactive environment.

High risk: Another option is to use a bulk explosive that contain urea, which itself is accepted throughout the industry as the prime inhibitor for use in reactive ground situations, and must be mandatory when reactivity is confirmed before drilling and blasting work commences on a designated block.

Physical separation: when using liners in a blasthole to reduce contact between the ammonium nitrate explosives and the surrounding reactive ground, it must be remembered that liners may not provide the necessary separation required. Liners have a tendency to rip and tear, especially under strain, and allow the explosives to leak into the potential reactive atmosphere. When physical separation is used as a means to reduce the risk of reaction in a reactive atmosphere, then is it still recommended that an inhibited explosive is used in the liners, as well as regular testing of the liners done, to ensure the effectiveness thereof.

6.2.4. Heat resistant initiating systems

It is very important to know the exact tested temperatures at which the current initiating systems supplied to the mine will possibly detonate. As these components are the most sensitive to heat and will most likely fire first, the maximum heat tolerances for the reactive ground management plan should be based on these limits.

If the tolerances are very low, the explosive suppliers should be contacted and a range of heat resistant initiating systems need to be presented for use in suspected reactive ground. When none is available from the current supplier, alternative sources should be investigated.

6.2.5. Blast Eye

It is recommended that the Blast Eye hot hole monitor, or similar device, be used on all blast blocks where reactive ground is suspected or confirmed. As seen in **Section 6.1.4** as well as in Chapter 5, **Section 5.8**, the monitor can be used in conjunction with the PVJ testing done throughout the blast block and placed in the holes as indicated in **Figure 36**.

The monitor will alert the blasting crew of any temperature variance above 60°C. This is when the blaster will know the block must be closed off and completed as soon as possible. The audible alarm above 80°C will alert to an extreme emergency, and evacuation of the block must take place and available holes fired.

6.2.6. Stemming

Both stemmed and un-stemmed holes are vulnerable to self-detonation in reactive ground. In extremely reactive areas, it is recommended that holes should not be stemmed. Even if the hole fires, it is more likely to deflagrate rather than detonate.

When stemming is required, the stemming material must be of an inert nature that will not affect or increase the reactivity in or around the blast hole. Drill chippings used as stemming material must be avoided at all cost.

If the environmental influence requires stemming, then the stemming volume must be planned such that it can be completed within the designated period to complete the preparations for the blast. The way in which a hole is stemmed can greatly influence the time required for completion of a blast block. Stemming material should be placed close to the blast block and placed where it can be easily accessed.

Any rapid stemming delivery system can be recommended that will allow the charged block to be stemmed very quickly.

The stemming of the holes should be done in such a way as to follow the charging of the holes. If a breakdown in the stemming delivery system should occur, all charging should be squared off as quickly as possible to allow stemming to be completed manually by hand or with whatever means available.

6.3. Planning

6.3.1. Technical planning - Sampling

Whether the mining area is a new green-fields site, or expanding brown-field operation, or the completion of the remainder of an existing reserve, a long term sampling regime must be drawn up. The formal sampling and testing for reactive ground should be included in the exploration drilling and sampling plan. As discussed in **Section 5.4**, major geological disturbances may influence the reactivity of the coal seam host rock, due to metasomatism, and therefore when these disturbances are discovered, the sampling of these areas should be intensified. The sampling routine for the site's Geological department must be very clear regarding sampling periods and intensity. The sampling routine should consist of:

- Sampling selected borehole cores for laboratory testing of reactivity.
- Sample routines for the active pit, using a pick to collect raw face samples for laboratory testing.

- Daily thermal pit surface monitoring of all faces where drilling and charging are taking place, or will take place in the near future.
- Thermal monitoring of PVJ cup samples as requested by the drill and blast crew.
- Thermal monitoring of charged blocks when preparing for a blast, as requested by the blaster, or when suspected reactive ground may occur.

6.3.2. Documenting and record keeping

A well-structured and transparent document control system must be in place to ensure that all information regarding reactive ground testing and monitoring be available for use as necessary by all site personnel.

The documents should include:

- Borehole sample results from core sampling.
- Mine plan indicating affected areas.
- Pre-emptive risk assessment documents.
- Proof of training and information sharing with individuals exposed to the risk.
- Observation records where the system is audited for compliance and shortcomings.
- Review records with amendments and communication records of these changes to all affected parties.

6.3.3. Technical planning – Defining the risk areas

There are two aspects that are important when defining risk areas with regards to reactive ground. The first step is to draw and update a mine plan.

As areas are identified where excessive sulphates could pose a risk, or where it is confirmed that reactive ground is present, should be recorded on a mine plan and displayed and distributed throughout the mine. Geological maps showing the sulphur content of the various coal seams cannot be used as a definite indicative tool. The reactivity of the host rock is highly dependent on the amount of leaching that distributed the sulphur upwards into the rock, and not the coal sulphur contents itself.

The defined areas indicating potential high risk should be displayed with a designated colour, and a separate indication for confirmed reactive areas. The plan must also highlight all related geological disturbances that may influence potential reactive ground risk environments. Indications must be made where actual reactive ground events were recorded on site.

These plans will warn the mining operations team when they are approaching these risk areas, and will therefore greatly assist in the risk-assessments they will need to perform prior to entering these areas.

The second step is physical demarcation in the pit with easily identifiable markers as agreed to by the involved parties. This will allow anyone entering, or working in the vicinity of the area, to be cognisant of the potential risk. If not covered in the pre-emptive risk assessment before entering the workings, it can be assessed in the pit and the appropriate steps taken.

6.3.4. Technical planning - Blast designs

The blast plan supplied by the blasting engineer should take the following into account when designing a blast in a possible reactive ground area:

- No detonators should be placed in a blast hole, due to their low temperature tolerance. Use only detonator cord with a booster to initiate the bulk explosive in the blast hole.
- The initiators should be left out of the hole for as long as possible. The hole should be primed from the top.
- If stemming isn’t critical due to vibration or noise issues, it should not be included in the planning and the blast allowed to be fired without stemming.
- If stemming is necessary, it should be done in a manner to allow the stemming to be completed with the charging of the blast, and not delay the initiation of the blast block. It is recommended that field tests be done to determine the current

stemming times and restrictions it will place on the size of the blast that can be completed in one shift. These cycle times should be kept on record to allow proper planning of the size of the blasts.

- If the explosive supplier can supply an inhibited bulk explosive that will delay the reaction of sulphides with ammonium nitrate, it should be planned to use it in every risk area.

6.3.5. Training and information sharing

Employees, contractors, explosive suppliers and all personnel that may be exposed to potential reactive ground, must be made aware of the risks involved and given all the possible information in managing the risk. The management teams must be aware of the procedures regarding the management of reactive ground and ensure that the information therein is disseminated throughout the organisational structures and implemented wherever their input or actions are relevant.

The personnel must be conversant with their responsibilities regarding their operating procedures, specific job responsibilities, all identified hazards and emergency procedures when dealing with reactive ground.

Procedures with regards to the systematic drilling, charging and priming of the holes must be created with inputs from the blasting crew and product specialists to ensure that a blast block can be charged and fired with the optimal use of available resources and with the least number of people necessary to reduce exposure risk. The procedure must take into account that the most heat sensitive part of the entire process is the initiating systems, and it is there that the greatest care should be taken to reduce exposure time to the reactive atmosphere to a minimum.

A training program must be implemented that will make every person involved in the process aware and conversant with all the rules regarding reactive ground. The program must take into account new personnel on site and continues refreshers and reassessment annually for all the involved parties.

6.3.6. Blast preparation

The first step in reducing the risk when dealing with reactive ground, is to reduce the time exposed to the risk as much as possible. The blasting protocol on site should include a line-up of every action and equipment and accessory required for the completion of the blast. All the requirements for the blast must be ticked off and be on standby for the charging and blasting of the area. Once the operation starts, every person must know his role and the operation should be completed in the minimum amount of time, within the same shift and with all emergency operating steps ready in case the temperature of the holes increase dramatically within the process.

6.3.7. Monitor and review

The procedures and actions must be revised periodically, unless a shortcoming is detected in the current procedure that will require immediate investigation and improvement amendments.

New technology must be investigated and included where necessary to reduce the risk as far as possible. Changes in geology must be noted and prompt a review. Possible changes in the blasting practices on site, or of the products used, must allow for a review of the procedures. Interviews with personnel exposed to, affected by, and dealing with the management of reactive ground, must be done to pick up any difficulties and opportunities that may decrease the risk associated with current practices.

Any changes to the procedures must be signed-off by all affected parties. The changes must immediately be worked into the training program and all persons dealing with, or being affected by the work in and around reactive ground, must be informed. By following these steps a continuous improvement process will be installed that will ensure the vigilance of the operation and the future implementation of improvements in the management of reactive ground.

CHAPTER 7 – CONCLUSION

7. FINAL CONCLUDING COMMENTS

Reactive ground is a severe safety risk in opencast coal mines as it is very difficult to predict and therefore difficult to manage. The key factor when considering reactive ground is exposure time to the elements and to ammonium nitrate based explosives. There should be a form of management control on the mine to minimize the hazards when blasting reactive ground.

The processes required to effectively minimise the risk, may increase the costs of blasting as well as the workload of the personnel involved in the blasting processes. However, this intervention is required if work is to be continued safely.

The steps recommended in this research report can guide the mine to produce an effective management strategy that will greatly reduce the risk personnel will be exposed to when experiencing reactive ground on site. The recommendations can be used to form the basis of a reactive ground procedure. This will assist in understanding, identifying, and reducing the risk involved in dealing with reactive ground, and reducing potential productivity delays, damage to equipment, and most importantly, it may save lives.

REFERENCES

Australian Explosives Industry and Safety Group Incorporated. 2007. *Elevated Temperature and Reactive Ground – Code of Practice.* [Online] Available: http://www.dmp.wa.gov.au/documents/Code_of_Practice/DGS_COP_ElevatedTempReactiveGround.pdf [2012, December 6]

Australasian Institute for Mining and Metallurgy, no. 228. 1968. Place of conference, (1968). *The reaction of ANFO explosives with mineral sulphides.* Lukaszewski, G.M. Place of publication, publisher.

AEL Mining Services. 2013. Blasting accessories, Hot hole monitor. [Online] Available: http://www.aelminingservices.com/blasting-accessories.html [2013, November 1]

AEL Mining services. 2013. *Detonating Cords Technical data sheet – Revision 2 – October 2011.* Johannesburg: AEL Mining Services

AEL Mining services. 2013. *Pentolite Primers Technical data sheet – Revision 3 – June 2013.* Johannesburg: AEL Mining Services

AEL Mining services. 2013. *SHOCK TUBE – MULTI SPD – Technical data sheet – Revision 3 – June 2013.* Johannesburg: AEL Mining Services

Bellairs, P. & Ash, M. 1995. Further improvements to a safe and efficient blasting procedure, in *Proceedings EXPLO '95 Conference,* 4-7 September, 1995*.* Brisbane: 63-66.

Bellairs, P., Hellyer, G., Scales, R., Travers, I. & French, D. 1999. Inhibited explosive versus liners to safely blast a reactive rock type at the Mt Whaleback iron ore mine. 1999G Volume 2. International Society of Explosives Engineers.

BME. 2008. *Explosives, Energy and performance*. BME training module 1 energy.doc. Surface blasting technology. BME, Member of the Omnia Group: Gauteng.

BME. 2007. *Vibration, air blast and fly rock*. Training module 5. Surface blasting technology. BME, Member of the Omnia group: Gauteng.

Bruinette, L. 2010. *Action plan in Reactive Ground. ICAM Goedgevonden*. Goedgevonden Colliery.

De Korte, J. 2013. *Coal Preparation and beneficiation* (*CHMT7058)*. Johannesburg: University of the Witwatersrand. (Class notes).

Delagey, M. 2010. Sasol Premature Detonation Report: TS 36/10. Unpublished report. Johannesburg: Sasol Nitro.

Goedgevonden. 2010. Blast report. OB 0422 0421. Goedgevonden Colliery

Han, X. Freij, S. Feng, B. Gunawan, R. Zhang, D & Waters, P. 2005. A chemical characterisation of pyritic black shales in an iron ore mine. Unpublished paper delivered at the Iron ore conference. 19 – 21 September, Fremantle, Western Australia.

Kennedy, B.J. & Tyson, N. 2001. Blasting in Reactive ground. EXPLO 2001, Hunter Valley, NSW. 28 – 31 October 2001, Hunter Valley, NSW: 53-61.

Lukaszewski, G.M. 1968. The reaction of ANFO explosives with mineral sulphides, in Conference Proceedings, Australasian Institute for Mining and Metallurgy, no. 228, December 1968: 61-70.

Ngomezulu, V. 2011. Correspondence: Internal Memo Reactive Ground. Goedgevonden Colliery

Orica Mining Services, 2013. *A briefing note on reaction ground - version 6.* [Online] Available: https://www.oricaminingservices.com/uploads/Briefing_Note_Reactive_Ground_Vers_6.pdf [2013, December 13]

Phillips, H., Uludag, S. & Chabedi, K. 2011. *Prevention and control of spontaneous combustion.* [Online] Available: http://miningandblasting.files.wordpress.com/2009/09/spontaneous_combustion_guidelines.pdf [2013, March 20]

Pulles, H & De Lange Incorporated. 2005. Goedgevonden Colliery EMP Amendment. Unpublished report. Goedgevonden Colliery.

Querol Aragón, E. García Torrent, J. & Cámara Rascón, A. *s.a.* Dep. Eng. Química y The heating process of combustable matter. Universidad Politécnica de Madrid

Rasnik, D. 2000. Auto-Catalysed Progression. [Online]. Available: http://www.vitaeauct.narod.ru/003/rct/0100.htm [2013, September 25].

Republic of South Africa. Department of Minerals and Energy. 2006. Mine Works Plan Goedgevonden Colliery. Unpublished report. Goedgevonden Colliery

Republic of South Africa. Department of Minerals and Energy. 2002. Environmental Management Program - OT6/2/2/448. Unpublished report. Goedgevonden Colliery.

Rorke, AJ. 2004. *Temperature sensitivity of HEF100 and HEF207 based on laboratory tests carried out on 13 July 2004*. BME001_2004.doc. BME.

Rorke, AJ. 2010. Report for Goedgevonden on HEF Stability in hot areas. Unpublished report. BME, Member of the Omnia group. Gauteng. 27 October 2010.

Rumball, J.A. 1991. The interaction of partially weathered sulphides in the Mt McRae Shale formation with ammonium nitrate. Unpublished doctoral dissertation. Western Australia: Murdoch University.

Statpac. 2013. Sampling methods. *s.a.* [Online] available: http://www.statpac.com/surveys/sampling.htm [2013, September 25].

Swanepoel, B. 2011. Managing explosives and burning coal. Unpublished presentation. AEL Mining Services. EMalahleni.

Van Jaarsveld, P. Van Greunen, P. 2013. Dealing with reactive ground. BME, a member of the Omnia group. BME conference 2013, Gauteng.

Appendix A: Skid Steer Cycle time study

Skid Steer cycle time test done at Goedgevonden Colliery Overburden Blast block

Cycle Time		
Area	GS0549	
Date	12/03/2010	
Time Measured in unit (hour:minute:second)		
Start time	End time	Total Cycle time
H:M:S	H:M:S	H:M:S
00:00:00	00:01:20	00:01:20
00:01:20	00:02:38	00:01:18
00:02:38	00:04:20	00:01:42
00:04:20	00:05:22	00:01:02
00:05:22	00:06:25	00:01:03
00:06:25	00:07:20	00:00:55
00:07:20	00:08:22	00:01:02
00:08:22	00:10:28	00:02:06
00:10:28	00:11:55	00:01:27
00:11:55	00:13:27	00:01:32
00:13:27	00:15:31	00:02:04
00:15:31	00:16:50	00:01:19
00:16:50	00:18:29	00:01:39
00:18:29	00:19:48	00:01:19
00:19:48	00:21:47	00:01:59
00:21:47	00:23:32	00:01:45
00:23:32	00:25:20	00:01:48
00:25:20	00:27:21	00:02:01
00:27:21	00:28:42	00:01:21
00:28:42	00:30:35	00:01:53
00:30:35	00:32:50	00:02:15
00:32:50	00:34:23	00:01:33
00:34:23	00:36:28	00:02:05
00:36:28	00:38:11	00:01:43
00:38:11	00:40:15	00:02:04
00:40:15	00:42:19	00:02:04
00:42:19	00:44:25	00:02:06
00:44:25	00:46:35	00:02:10
00:46:35	00:48:40	00:02:05
00:48:40	00:50:58	00:02:18
00:50:58	00:52:20	00:01:22
00:52:20	00:54:28	00:02:08
00:54:28	00:56:39	00:02:11
00:56:39	00:58:21	00:01:42
00:58:21	01:00:01	00:01:40
01:00:01	01:01:10	00:01:09
Average time per trip (hour:minute:second)		00:01:42
Average time per hole (hour:minute:second)		00:05:06

Notes:
140m Blast block
3 heaps stemming outside blast perimeter
Weather warm clear slight dusty
3 trips stemming per hole
Stemming length planned 5m

Appendix B: Stemming truck cycle time study

Stemming Truck cycle time test done at Goedgevonden Colliery Overburden Blast block

	Cycle Time		
	Area	GS0636	
	Date	25/04/2010	
	Time Measured in unit (hour:minute:second)		
	Start time	End time	Total Cycle time
	H:M:S	H:M:S	H:M:S
1	00:00:00	00:00:20	00:00:20
2	00:00:20	00:00:47	00:00:27
3	00:00:47	00:01:12	00:00:25
4	00:01:12	00:01:35	00:00:23
5	00:01:35	00:02:00	00:00:25
6	00:02:00	00:02:25	00:00:25
7	00:02:25	00:03:03	00:00:38
8	00:03:03	00:03:33	00:00:30
9	00:03:33	00:03:59	00:00:26
10	00:03:59	00:04:24	00:00:25
11	00:04:24	00:04:47	00:00:23
12	00:04:47	00:05:10	00:00:23
13	00:05:10	00:05:34	00:00:24
14	00:05:34	00:05:54	00:00:20
15	00:05:54	00:06:24	00:00:30
16	00:06:24	00:32:07	00:25:43
17	00:32:07	00:32:45	00:00:38
18	00:32:45	00:33:11	00:00:26
19	00:33:11	00:33:35	00:00:24
20	00:33:35	00:33:58	00:00:23
21	00:33:58	00:34:21	00:00:23
22	00:34:21	00:34:46	00:00:25
23	00:34:46	00:35:08	00:00:22
24	00:35:08	00:35:31	00:00:23
25	00:35:31	00:35:54	00:00:23
26	00:35:54	00:36:20	00:00:26
27	00:36:20	00:36:42	00:00:22
28	00:36:42	00:37:09	00:00:27
29	00:37:09	00:37:31	00:00:22
30	00:37:31	00:37:56	00:00:25
31	00:37:56	00:38:20	00:00:24
32	00:38:20	00:38:53	00:00:33
33	00:38:53	01:07:10	00:28:17
34	01:07:10	01:07:39	00:00:29
35	01:07:39	01:08:03	00:00:24
36	01:08:03	01:08:26	00:00:23
37	01:08:26	01:08:49	00:00:23
38	01:08:49	01:09:12	00:00:23
39	01:09:12	01:09:36	00:00:24
40	01:09:36	01:10:01	00:00:25
41	01:10:01	01:10:26	00:00:25
42	01:10:26	01:10:51	00:00:25
43	01:10:51	01:11:16	00:00:25
44	01:11:16	01:11:42	00:00:26
45	01:11:42	01:12:12	00:00:30
46	01:12:12	01:12:37	00:00:25
47	01:12:37	01:12:58	00:00:21
48	01:12:58	01:13:27	00:00:29
49	01:13:27	01:13:56	00:00:29
50	01:13:56	01:14:20	00:00:24
51	01:14:20	01:37:15	00:22:55
52	01:37:15	01:37:37	00:00:22
53	01:37:37	01:38:04	00:00:27
54	01:38:04	01:38:29	00:00:25
55	01:38:29	01:39:01	00:00:32
56	01:39:01	01:39:36	00:00:35
57	01:39:36	01:40:00	00:00:24
58	01:40:00	01:40:24	00:00:24
59	01:40:24	01:40:49	00:00:25
60	01:40:49	01:41:15	00:00:26
61	01:41:15	01:41:44	00:00:29
62	01:41:44	01:42:06	00:00:22
63	01:42:06	01:42:21	00:00:15
64	01:42:21	01:42:47	00:00:26
65	01:42:47	01:43:11	00:00:24
66	01:43:11	01:43:35	00:00:24

Notes:
300m interburden Blast Block
Stemming collect from dump site
Planned stemming length 5m
Start recording with full load ready for blaster and attendants