# A CRITICAL INVESTIGATION INTO SPONTANEOUS COMBUSTION IN COAL STORAGE BUNKERS

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Presented in partial fullfilment of the requirements for the degree

**MSc (Applied Science) Mining**

**IN THE FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY**

**DEPARTMENT OF MINING ENGINEERING**

UNIVERSITY OF PRETORIA

**1 DECEMBER 2015**

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# ABSTRACT

# A CRITICAL INVESTIGATION INTO SPONTANEOUS COMBUSTION IN COAL STORAGE BUNKERS

## SGOVENDER

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| Degree: | MSc (Applied Science) Mining |

In coal mining, spontaneous combustion can occur in many areas such as stockpiles, underground workings, waste dumps, coal faces, in-pit ramps and backfill areas. Spontaneous combustion has been defined as an oxidation reaction, which occurs without an external heat source. Although not limited to coal, the most significant hazard of spontaneous combustion is the fires that occur in coal mining operations around the world. These fires pose a serious risk to the safety of workers in the coal mines. This phenomenon also has an environmental impact, which can affect the quality of life for future generations.

Extensive research work has been done and recorded about spontaneous combustion in coal stockpiles, dumps and coal faces, but very limited work has been conducted on raw coal storage bunkers. This study investigated the occurrence of spontaneous combustion in coal storage bunkers, and established that there is no single document available that addresses the problem adequately. Therefore, a need was identified to create a guideline with decision analyser steps to be able to arrive quickly at a possible solution to the problem.

This work does not address spontaneous combustion in underground workings, waste dumps, stockpiles, coal faces, in-pit ramps and backfill areas.

It was found that important factors affecting the possibility of SC occurring were the type of coal being supplied to the bunker, the mining practice with regard to the standing time of the

loose cubic metres of coal on the mining benches, and the impact of the physical factors around the bunker.

The information obtained could be of great significance when designing or trying to solve spontaneous combustion problems in raw coal storage bunkers. The guideline and decision analyser steps can be applied early in the phase of the project in order to minimise or eliminate similar mistakes made in the industry over the years.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| ANFO | Ammonium nitrate fuel oil |
| C | Carbon |
| $CH_4$ | Methane |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| CPT | Crossing Point Test |
| CSIR | Council for Scientific and Industrial Research |
| CV | Calorific value |
| °C | Degrees Celsius |
| DMR | Department of Minerals and Energy |
| DSC | Differential scanning calorimeter |
| DTA | Differential thermal analysis |
| ECE | Economic Commission for Europe |
| GG | Grootegeluk |
| GMEP | Grootegeluk Medupi Expansion Project |
| GMJ | Giga-megajoule |
| ha | Hectare |
| $H_2$ | Hydrogen |
| $H_2O$ | Water |
| $H_2S$ | Hydrogen sulphide |
| IMO | International Maritime Organization |
| kg/sq. m | Kilograms per square metre |
| $kJ\ mol^{-1}$ | Kilojoules per mole |
| km | Kilometre |
| kt | Kiloton |
| KPI | Key Performance Indicators |
| LCM | Loose cubic metres |
| LEL | Lower Explosive Limit |
| MJ/kg | Megajoules per kilogram |
| Mtpa | Megatons per annum |
| $Mm^3$ | Million cubic metres |

| | |
|---|---|
| mmHG | Millimetres of mercury |
| mt | Million tons |
| $NO_x$ | Nitrogen oxides |
| $O_2$ | Oxygen |
| $\Delta P$ | Change in pressure |
| RBCT | Richards Bay Coal Terminal |
| RD | Relative density |
| RIT | Relative ignition temperature |
| ROM | Run of mine |
| RSF | Reactive semifusinite |
| SA | South Africa |
| SC | Spontaneous combustion |
| $SO_2$ | Sulphur dioxide |
| TG | Thermogravimetry |
| USBM | United States Bureau of Mines |

# CHAPTER 1
# MOTIVATION FOR THIS STUDY

This chapter highlights the need for the investigation and quantifies the seriousness of the situation. It also outlines the objectives of the study, as well as the approach in achieving these objectives.

## 1.1    MINE BACKGROUND AND GENERAL INFORMATION

The Grootegeluk (GG)Coal Mine ("the Mine") is located within the boundaries of the Lephalale Magisterial District in Limpopo, South Africa. It is situated 18km west of the town, covering a surface area of approximately 6528ha. In general, the Mine is accessed from the west via a sealed tarred road, linking it with Onverwacht. This, in turn, is connected with the rest of the towns colloquially referred to as the Bushveld, that is Thabazimbi (120 km to the south), Modimolle (formerly Nylstroom, 150 km to the south-east) and Makopane (formerly Potgietersrus, 160 km to the east-south-east) via tarred roads(see Figure 1.1) (Wieruszowski & Stander 2008).

A portion of the Mine's product is railed from site by a single-gauge railway line extending southwards to Thabazimbi. A softly undulating contour dominates the mining lease area. This is a prominent attribute of the coal deposit located within the Waterberg. It was the effect of the low-angled dipping Permian coal-bearing strata that resulted in the undulating relief(Wieruszowski & Stander 2008).

On a regional scale, the Mine lies within the summer rainfall district of the Bushveld, between the Matlabas and Mokolo Rivers which meander through the region, channelling precipitation northwards into the ephemeral Limpopo River(Wieruszowski & Stander 2008).

The Mine is a multi-bench opencast coal mine in the shallow coal portion of the Waterberg Coalfield. A series of parallel benches advance in a westward direction, progressively across the deposit via a process of drilling and blasting, loading and hauling with truck-and-shovel fleets. Electric rope shovels are used for pre-stripping of the soft, mainly clayey, overburden. Access to the different benches is via a series of inclined ramps, arranged in a diverging manner

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from the pit top, situated along the northern and southern pit limits. Inter-burden rock is gradually dumped as backfill material in the pit. The Mine has developed into a multi-product operation that produces thermal and metallurgical coal in addition to semi-soft coking coal, with an overall yield of around 50%.
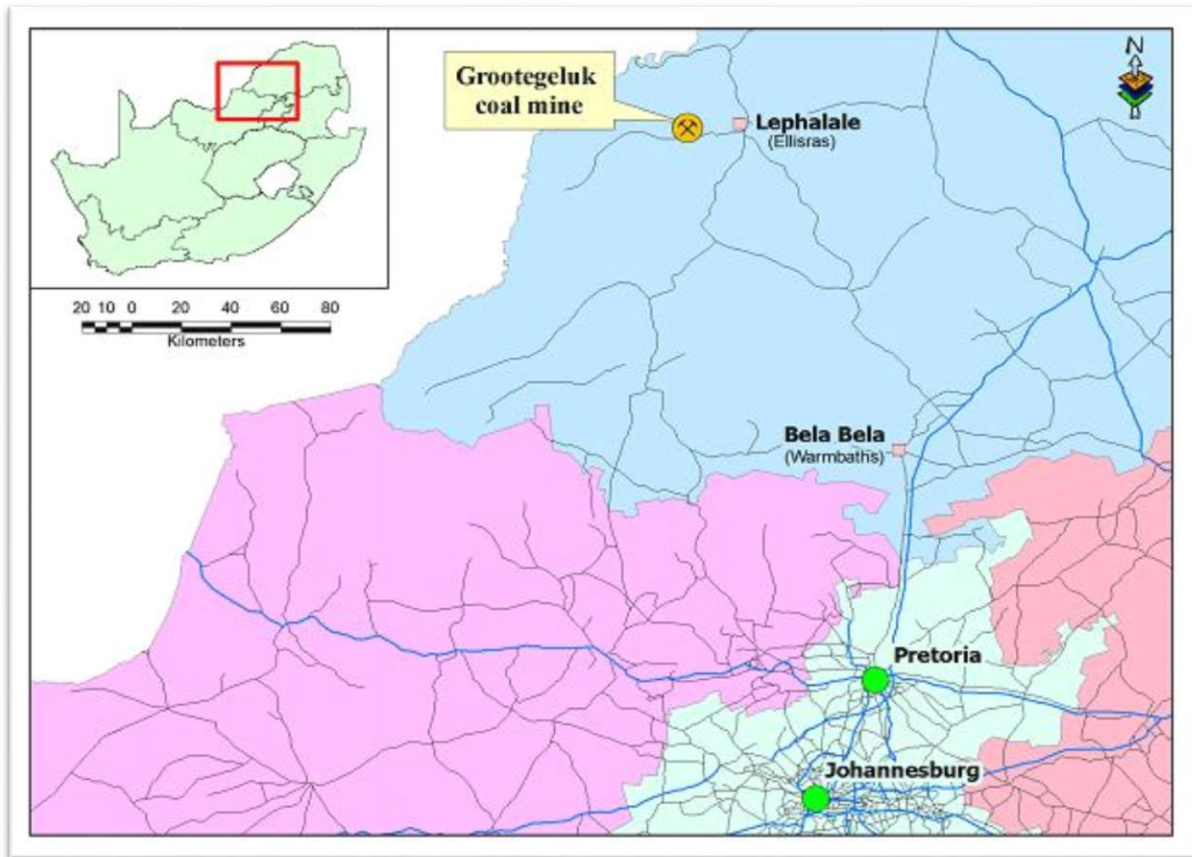


**Figure 1.1a: Location of Grootegeluk Mine(Wieruszowski & Stander, 2008)**

The Mine is at present a conventional truck-and-shovel mining operation and the existing mining footprint covers an area of more than 800 ha. The primary loading equipment consists of both rope and hydraulic shovels. The rope shovels are used on the five upper coal benches and the hydraulic shovels for the selective mining of the pit bottom benches 6 to 11. The present haul truck fleet consists of rear-dump trucks in the 185–250 ton class, which currently transport an average of 57 million tons annually. Once the GG Medupi Expansion Project (GMEP) reaches full production, this will increase to an average of 130–140 million tons annually.

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The haul trucks are diesel-electrically driven and also equipped with a pantograph system, making it possible to utilise electrical power when driving on the ramp out of the pit. In this way, diesel consumption is minimised, productivity increased and noise pollution reduced. Diesel-driven rotary drills are used to drill the blast holes. Blasting is performed using water-resistant heavy ammonium nitrate fuel oil(ANFO) explosives.

The Mine uses a computerised truck-dispatching system to manage and optimise the mining operations and to ensure that the material from the different benches is delivered to the right plant at the right time.

### 1.1.1    The Waterberg-Grootegeluk ore body

The Waterberg Coalfield has an approximate 88 km east-west strike length, complemented by a north-south width of ± 40 km (Figure 1.1b), but extends further westward into Botswana.

The Coalfield is fault-bounded along its southern and northern margins and could be referred to as a graben deposit (extensional tectonic environment). In the south, the east-west striking Eenzaamheid Fault forms the southern limit of the coalfield.

Rocks belonging to the Waterberg Group (Mogalakwena Formation) occur south of this fault. In the north, the east-west striking Zoetfontein Fault depicts the northern limit, with Archaean granite outcrops occurring north of this fault (Faure, Willis & Dreyer 1996).
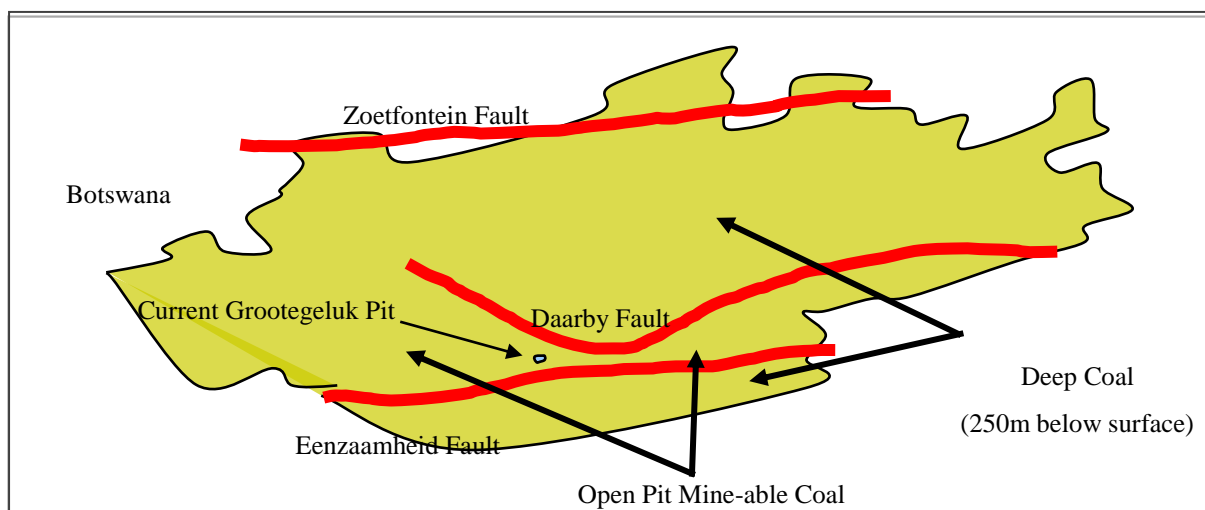


**Figure 1.1b: The Waterberg coalfield (Roux 2014)**

The Grootegeluk ore body is located in the Ecca Group as part of the stratigraphy of the Karoo Sequence and separated into Volksrust formation and Vryheid formation.

In the Volksrust Formation the upper part of the coal bearing strata comprises intercalated shale and bright coal layers with an average thickness of ± 60 m. It displays such a well-developed repetition of coal-shale assemblages that it could be divided into seven sedimentation cycles or Zones (Table 1.1a). The Volksrust Formation has been classified as a thick interbedded seam deposit type according to the South African Mineral Resource Committee (SAMREC) Code.

**Table 1.1a: Schematic representation of lithology (Roux 2014)**

| | COAL ZONES & SAMPLES | | AVERAGE THICKNESS (m) | % COAL (in situ) | LITHOLOGY |
|---|---|---|---|---|---|
| | | GROOTEGELUK COAL MINE - COAL ZONES | | | |
| **V O L K S R U S T  F O R M A T I O N** | Overburden Samp. 1a-b | | 16.50 | | Sand and topsoil (~1m) with scattered ferricrete and calcrete nodules, yellow brown mudstone, massive and weathered in top half, light gray mudstone and bright coal bands in bottom half. |
| | ZONE 11 Samp. 1c-d | | 7.56 | 38.33 | Bright coal interbedded with gray mudstone, carbonate lenses, no siderite present. |
| | ZONE 10 Samp. 2-6 | | 9.37 | 53.86 | Bright coal interbedded with carbonaceous shale/mudstone, carbonate lenses, small amount of siderite present, thick mudstone present in bottom half. |
| | ZONE 9 Samp. 7-9 | | 6.53 | 48.34 | Bright coal with prominent siderite present at base, interbedded with carbonaceous shale/mustone. Thick coal seam. |
| | ZONE 8 Samp.10-14 | | 9.04 | 42.82 | Bright coal with prominent siderite present at base, interbedded with carbonaceous shale/mudstone.  Thick coal seam at base. |
| | ZONE 7 Samp. 15-18 | | 10.15 | 39.94 | Bright coal, sideritic, interlayered and interlaminated with carbonaceous shale/mudstone. |
| | ZONE 6 Samp.19-21 | | 6.54 | 32.17 | Bright coal, very sideritic at bottom, interlaminated with carbonaceous shale/mudstone. |
| | ZONE 5 Samp. 22A-22FS | | 13.54 | 21.97 | Carbonaceous shale/mudstone, thin coal bands present in bottom two-thirds, less prominent siderite content, 2,5m coal-rich shale at base. |
| **V R Y H E I D  F O R M A T I O N** | ZONE 4 Samp.23 | | 4.02 | 99.13 | Dull coal, interlaminated with bright coal in bottom portion, few thin shale bands present. |
| | Interburden | | 4.28 | | Mudstone, dark grey, with fossil bearing siltstone at base. |
| | ZONE 4A | | 1.52 | 96.37 | Dull coal, few thin bright coal laminae and few thin shale bands. |
| | Interburden | | 4.28 | | Mudstone, dark grey. |
| | ZONE 3 Samp.25-29 | | 7.82 | 96.41 | Dull coal with bright coal laminae present in bottom 1,6m portion, low ash content, few thin shale bands. |
| | Interburden | | 4.10 | | Sandstone, medium to coarse grained, few thin shale bands present, few thin coal laminae at top. |
| | ZONE 2 Samp.30-31 | | 3.73 | 98.22 | Dull coal, bright coal laminae present in the bottom 2m portion, low ash content, show coking characteristics. |
| | Interburden | | 13.85 | | Sandstone, medium to coarse grained, few thin shale bands present, thin coal laminae at top. |
| | ZONE 1 | | 1.53 | 98.34 | Dull coal, few coal laminae and thin shale bands. |

Smaller sub-cycles are contained within these Zones. These smaller sub-cycles have been sampled individually during exploration of the deposit. The terms "Zone" and "Sample" are

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being used at GG instead of "seam" and "ply" due to the site-specific intercalated nature of the coal and shale.

The Volksrust Zones typically start with bright coal at the base, with the ratio of coal: shale decreasing from the base of each Zone upwards. The basal Zone 5 is the exception because the coal is being evenly distributed throughout this Zone. The Volksrust shales show an increase in carbon content with depth and range from a massive bluish-grey mudstone at the top to carbonaceous shale towards the basal Zone (Faure *et al*. 1996).

Although the thickness and coal quality of the Volksrust Formation is reasonably constant across the coalfield, a large variation in the yield of semi-soft coking coal occurs vertically in the coal succession.

The Vryheid Formation (± 55 m thick) forms the lower part of the coal deposit and comprises of carbonaceous shale and sandstone with interbedded dull coal seams varying in thickness from 1.5 to 9.0 m. It has been classed as a multiple seam deposit type according to the SAMREC Code. There are five coal seams or Zones in the Vryheid Formation, which comprises of predominantly dull coal, with some bright coal developed at the base of Zones 2, 3 and 4. Due to lateral changes in the depositional environment, these Zones are characterised by a large variation in thickness and quality. Zone 3 is the best-developed dull coal zone within the mine lease area and reaches a maximum thickness of 8.9 m. The basal portion of this Zone yields a small fraction, which has semi-soft coking coal properties.

Zone 2 is, on average, 4 m thick and reaches a maximum thickness of 6 m in the mine lease area. The basal portion of this Zone also yields a fraction that has semi-soft coking coal properties. Zone 2 is the most constant of all the Vryheid coal Zones across the entire Waterberg Coalfield, with regard to thickness. Zone 1, the basal Vryheid coal zone, has an average thickness of 1.5m. Both the Volksrust and Vryheid Formation Zones are subdivided into sampling units (Table 1.1a), which are analysed in detail (Faure *et al*. 1996).

## 1.1.2    Bench layout and feed to plants

The bench layouts were established from the ore body of the Waterberg coalfields. The different zones as mentioned in Table 1.1a and corresponding benches are set out in Figures1.1c and 1.1d. The mine pit has been separated into 13 benches. The depth of the mine is approximately 132m from surface. Benches 2, 3, 4, 5 and 7B are being fed as run of mine material to the large washing plants referred to the GG plant 2 and 8 as indicated in Figure 1.1c. The large washing plants are being used to remove the intercalated material from the coal.

Benches 6 and 9A are fed as run of mine (ROM) material to dry plants for simple crushing and screening as indicated in Figure 1.1d. The material from these benches is being blended with the coal from GG plant 2 and 8 to reduce the moisture content for the "power station coal".

The production plan was used to establish the coal feed from the different benches to the different processing plants.

| | COAL ZONES & SAMPLES | BENCH HEIGHT (m) | GROOTEGELUK MINE BENCHES |
|---|---|---|---|
| **V O L K S R U S T   F O R M A T I O N** | Overburden Samp. 1a-b | 15.8 | BENCH 1 Rd=2.5g/cm³ |
| | ZONE 11 Samp. 1c-d | | |
| | ZONE 10 Samp. 2-6 | 13.5 | BENCH 2 Rd=1.74g/cm³ |
| | ZONE 9 Samp. 7-9 | 16.1 | BENCH 3 Rd=1.86g/cm³ |
| | ZONE 8 Samp.10-14 | | |
| | ZONE 7 Samp. 15-18 | 16.9 | BENCH 4 Rd=1.86g/cm³ |
| | ZONE 6 Samp.19-21 | | |
| | ZONE 5 Samp. 22A-22FS | 16.7 | BENCH 5 Rd=1.88g/cm³ |
| **V R Y H E I D   F O R M A T I O N** | ZONE 4 Samp.23 | 4.1 | BENCH 6 Rd=1.65g/cm³ |
| | Interburden | 5.7 | BENCH 7A Rd=2.21g/cm³ |
| | ZONE 4A | 1.4 | BENCH 7B  Rd=1.8g/cm³ |
| | Interburden | 3.7 | BENCH 8 Rd=2.45g/cm³ |
| | ZONE 3 Samp.25-29 | 8.2 | BENCH 9A&B Rd=1.64 + 1.53g/cm³ |
| | Interburden | 4.1 | BENCH 10 Rd=2.49g/cm³ |
| | ZONE 2 Samp.30-31 | 4.3 | BENCH 11 Rd=1.52g/cm³ |
| | Interburden | 13.85 | Typical Pit Floor (Occasional sumps for de-watering purposes) BENCH 12 Rd=2.5g/cm3 |
| | ZONE 1 | 1.55 | BENCH 13  Rd=1.6g/cm3     Possible Highwall Mining |

Plant GG2 & GG 8

**Figure 1.1c: Bench distribution to plants GG2 & GG8 (Roux 2014)**

GROOTEGELUK MINE BENCHES

| | COAL ZONES & SAMPLES | BENCH HEIGHT (m) | |
|---|---|---|---|
| V O L K S R U S T   F O R M A T I O N | Overburden Samp. 1a-b | 15.8 | BENCH 1 Rd=2.5g/cm$^3$ |
| | ZONE 11 Samp. 1c-d | 13.5 | BENCH 2 Rd=1.74g/cm$^3$ |
| | ZONE 10 Samp. 2-6 | | |
| | ZONE 9 Samp. 7-9 | 16.1 | BENCH 3 Rd=1.86g/cm$^3$ |
| | ZONE 8 Samp.10-14 | | |
| | ZONE 7 Samp. 15-18 | 16.9 | BENCH 4 Rd=1.86g/cm$^3$ |
| | ZONE 6 Samp.19-21 | | |
| | ZONE 5 Samp. 22A-22FS | 16.7 | BENCH 5 Rd=1.88g/cm$^3$ |
| V R Y H E I D   F O R M A T I O N | ZONE 4 Samp.23 | 4.1 | BENCH 6 Rd=1.65g/cm$^3$ |
| | Interburden | 5.7 | BENCH 7A Rd=2.21g/cm$^3$ |
| | ZONE 4A | 1.4 | BENCH 7B Rd=1.8g |
| | Interburden | 3.7 | BENCH 8 Rd=2.45g/cm$^3$ |
| | ZONE 3 Samp.25-29 | 8.2 | BENCH 9A&B Rd=1.64 + 1.53g/cm$^3$ |
| | Interburden | 4.1 | BENCH 10 Rd=2.49g/cm$^3$ |
| | ZONE 2 Samp.30-31 | 4.3 | BENCH 11 Rd=1.52g/cm$^3$ |
| | Interburden | 13.85 | Typical Pit Floor (Occasional sumps for de-watering purposes) BENCH 12 Rd=2.5g/cm3 |
| | ZONE 1 | 1.55 | BENCH 13  Rd=1.6g/cm3    Possible Highwall Mining |

Plant GG3 & GG 7

**Figure 1.1d: Bench distribution to plants GG3 & GG7 (Roux 2014)**

### 1.1.3    Mining process to bunker

The different benches as indicated in Figures 1.1c and 1.1d are being blasted into loose cubic metres (LCM) and then loaded with large rope or hydraulic shovels on haul trucks of approximately 180–240 tons. The haul trucks transport and dump the material into crushers. The material comes off the crusher and is being transported via conveyor belts to the storage bunker as indicated in Figures 1.1e and 1.1f. The bunker is separated into two compartments

as indicated in Figure 1.2b. The GG 8 raw coal is stored in the bunker to a maximum volume of 30.5 kt and the GG 7 raw coal is stored in the bunker to a maximum volume of 17.5 kt. This total volume of material can feed the plants for a maximum of eight hours continuously.
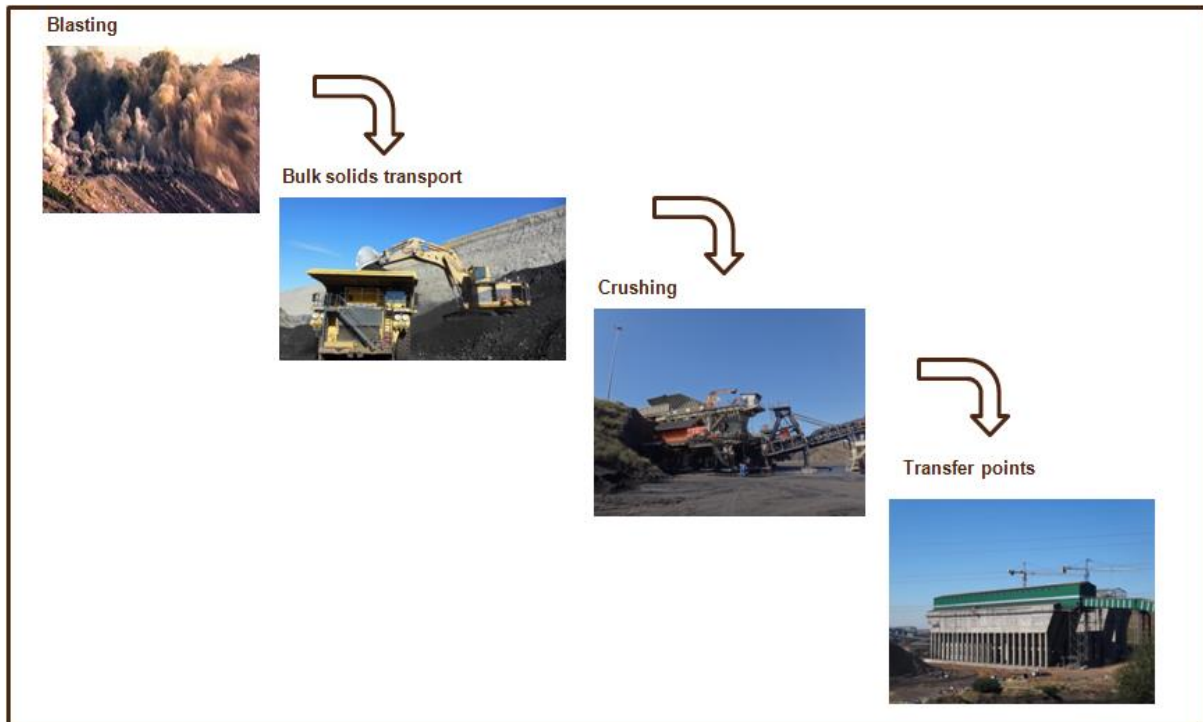


**Figure 1.1e: Mining process from benches to the bunker**
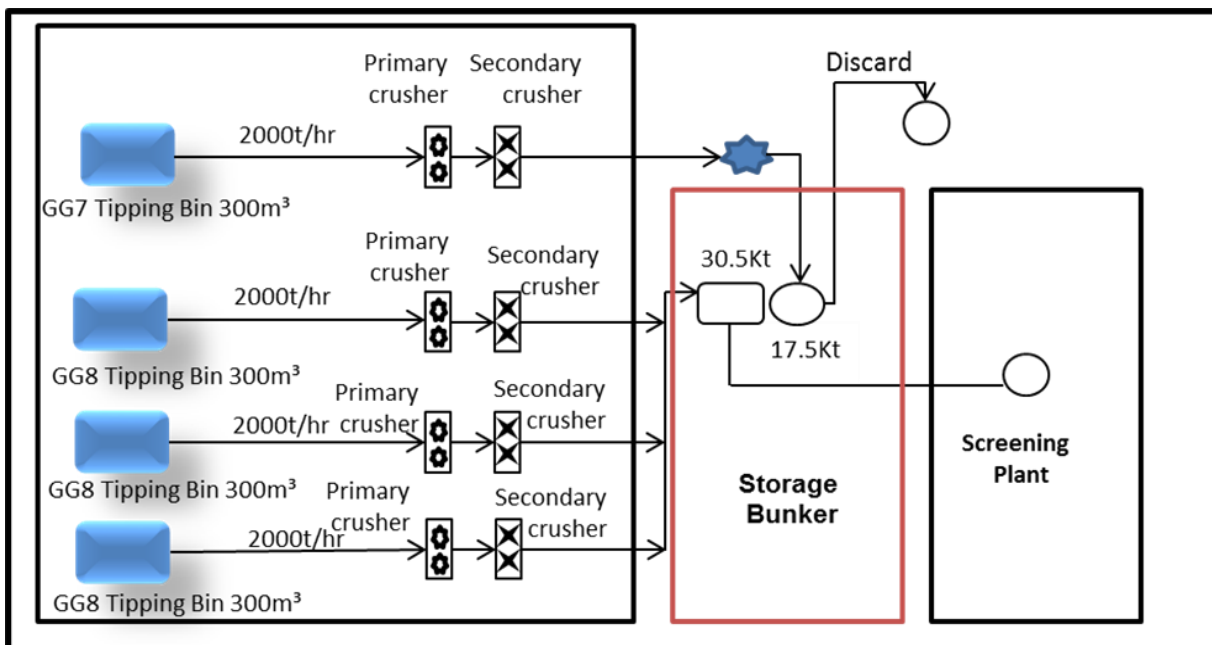


**Figure 1.1f: Process from crushers to the screening plant**

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## 1.2    PROJECT BACKGROUND

In a surface mine, it is frequent practice to have haul trucks dumping material into a tipping bin in a continuous sequence, or from a stockpile of coal when it is positioned close to the tip. From here a front-end loader collects the material from the stockpile and tips it into a tipping bin. If one of the trucks has a breakdown for an extended period, the loading sequence is interrupted and the processing facility tends to run out of material for processing. This type of scenario reduces the overall effectiveness of the equipment.

Mining is usually a batch process and the processing plant is a continuous operation, as set out in Figure 1.2a. The cost of capital to produce an additional ton of product on a plant once it has reached its optimised setpoint is much greater than the cost of capital to extract an additional ton of coal in the mining operation. In the mining operation, a truck can be added to increase the number of tons mined more rapidly and at a lower capital cost than would be the case to upgrade the plant complex.

Therefore, it becomes important to make sure that the mine's constraint is the plant process and that the plant is used optimally. In practice, it is difficult to optimise the plant process if there is instability in the system. It would be ideal to first stabilise, and then to optimise the plant process.
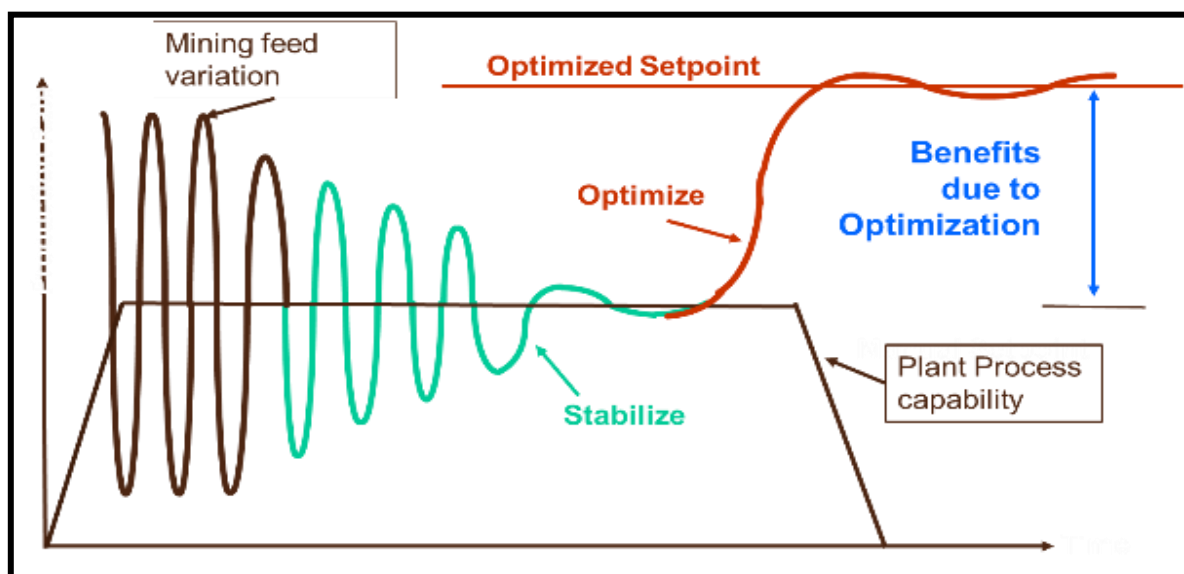


**Figure 1.2a: Mining feed variation vs plant process capability**

It then becomes important for the plant to operate at maximum capacity and at a greater overall equipment effectiveness to ensure that the number of tons per hour is maximised and the cost is kept as low possible. In order to achieve this, statistical fluctuations and interdependence must be eliminated from the mining operation. One of the solutions to this problem is to install a storage bunker between the mining operation and the plant.

During the design of the new GMEP the process design team recommended that a coal storage bunker be installed at the beginning of the plant process to ensure that the plant is fed with raw material continuously and at a stable feed rate. This will reduce dependence on continuous product feed from the mine.

The new coal processing plants designed at the GMEP have raw coal storage bunkers for each plant, with a storage capacity of either 17.5 kt or 30.5 kt. This equates to a storage capacity of 8 h of continuous production per plant (Figure 1.2b).

The overall GMEP facility is designed to produce 14.6 Mt of power station coal per annum, equivalent to an annual energy supply of 300 GMJ. This coal will supply the new Medupi Power Station once the project is completed. The Mine completed the expansion project in November 2014 and is currently engaged in the ramp-up phase of the project.

During the ramp-up phase in June 2012, spontaneous combustion occurred in the storage bunkers. Spontaneous combustion takes place when an oxidation reaction occurs without an external heat source. Heat generates spontaneously within an oxidised substance when dissipation of the heat generated cannot take place. Currently, the SC problem has been reduced to a bare minimum or zero-event scenario. This was achieved by ensuring that proactive measures were put in place to manage the situation. These proactive measures have been included in this report.

During the design process, there was limited reference material available for addressing the possibility of spontaneous combustion in such a large bunker (Gerber 2014). The work of Dr Stefan Antoni Adamski was apparently used as a guide to address any potential spontaneous combustion issues in the design. The author, however, established that Adamski's work

actually addressed the "Prevention of spontaneous combustion in back-filled waste material at the GG Mine" (Adamski 2003) and not spontaneous combustion in storage bunkers.
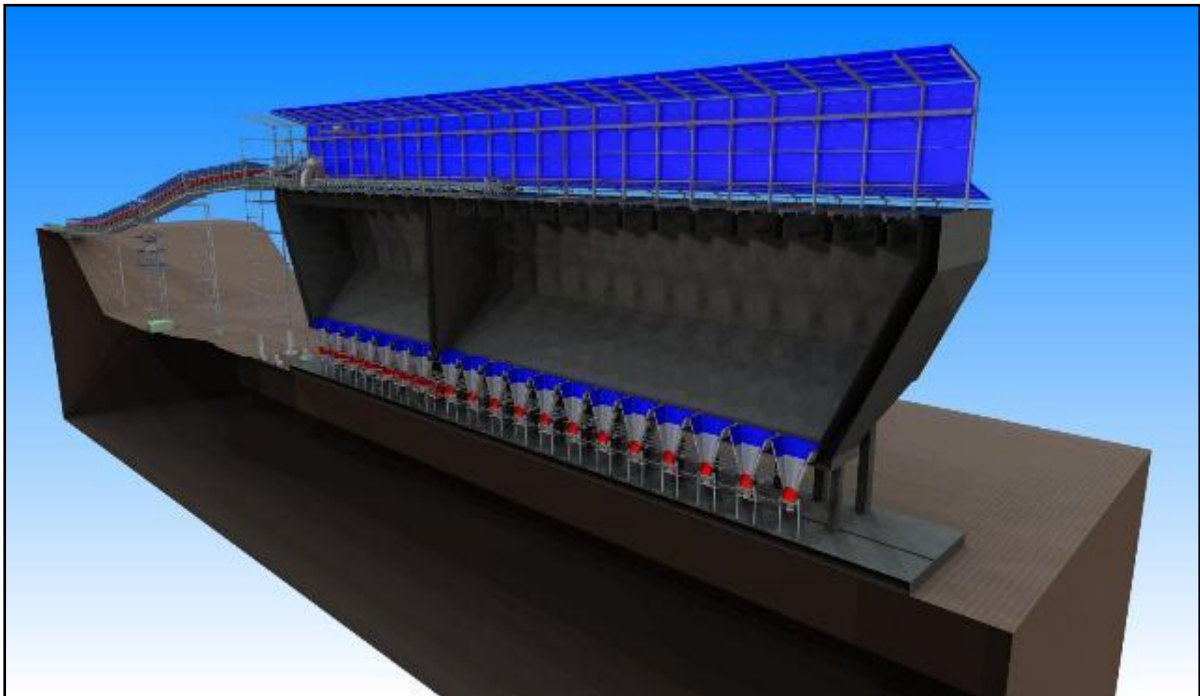


**Figure 1.2b: Raw coal storage bunkers (Moolman2010)**

Spontaneous combustion is a problem that has been investigated extensively before (for coal stockpiles, dumps and coal faces). However, each mine has its own unique problems, which need to be addressed accordingly. There has been limited material/research relating to spontaneous combustion in coal bunkers or coal silos. Accordingly, the main purpose of this study was to research this specific area of spontaneous combustion.

A risk assessment was done using a 5 x 5 risk matrix (Appendix A) to assess the current problem. An initial risk rating of 22 was achieved, which is extremely high. The implementation of control measures reduced the risk rating to 15, which was still high, but it did not eliminate the risk (Table 1.2). The definition of a "long period" in Table 1.2 refers to a period that is longer than 3 days.

**Table 1.2: Risk rating results (Nokwe 2014)**

| HAZARD IDENTIFICATION | | RISK ASSESSMENT | | RISK ANALYSIS | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | Risk Identification | Risk Analysis | Initial Risk Evaluation | | | Risk Type | | | | | | Risk re-evaluation |
| Geographical Area | Hazard Identification | Risk (Unwanted event) | Risk Consequences (Descriptive) | Consequence | Probability | Risk Rating | Health | Safety | Environment | Controls | Consequence | Probability | Residual Risk |
| ROM Bunkers / ROM Silos | Coal left for a long period in the bunker may lead to spontaneous combustion. | Equipment may be damaged by fire. | Loss of property. | 5 | 3 | 22 | | x | x | 1.Gas monitoring | 5 | 1 | 15 |
| | | People may be injured by fire. | Fatalities due to burn injuries | 5 | 3 | 22 | x | x | | 2. The principle of producing is first in first out | 5 | 1 | 15 |
| | | People may be exposed to gases (Gassing) | Fatalities due to gassing. | 5 | 3 | 22 | x | | x | 3. Permanent gas monitors | 5 | 1 | 15 |
| | | Explosion | Loss of property. | 5 | 3 | 22 | | x | x | 4. Material should not lie in the bunker for more than necessary | 5 | 1 | 15 |
| | | Explosion | Fatalities due to injuries from the explosion. | 5 | 3 | 22 | | x | x | 5. Material to be removed if plant is down for extended periods of time | 5 | 1 | 15 |

It was suggested that the bunker should be loaded from a shuttle car moving in sequence from right to left on the eastern side for plant GG8 and from left to right on the western side for plant GG7. The bunker should be kept at between 73 and 79% capacity, but should never exceed 85%. The space between 85% and 100% full capacity is a buffer zone which is provided to ensure that the plant can do a control stop when required. A control stop is programmed in such a way that the conveyor belts run until all remaining coal on the belt has been off-loaded into the bunker. Therefore, when the conveyor starts up again it does not start under load conditions. However, due to problems experienced with the shuttle car and the need to ensure that coal covers all draw-off points to prevent oxygen from entering the bunker, this sequence of loading could not be realised (Gerber 2012). Figure 1.2c shows a side view of the storage bunker.
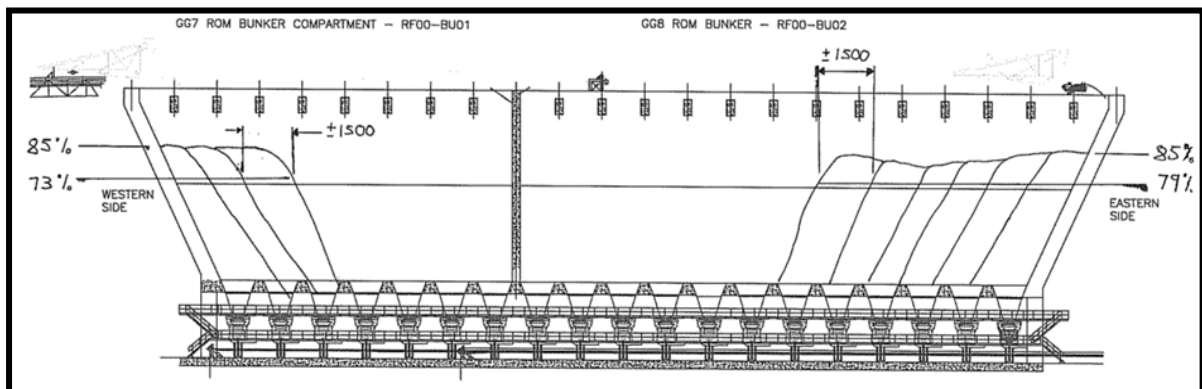


**Figure 1.2c: Side view of the coal storage bunker (Gerber 2012)**

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The coal supplied to different power stations varies significantly in terms of quality, i.e. calorific value and ash content. Power stations such as Lethabo, Kendal, Matla, Matimba and Majuba use coal with a CV range of between 18.3 MJ/kg and 21 MJ/kg, whereas Kriel, Hendrina, Tutuk, Duvha, Arnot, Camden, Komati and Grootvlei use coal with a CV range > 21.5 MJ/kg (Bester 2012). Moreover, the cost of coal supplied to the different power stations also differs due to certain factors such as mining methods, processing options and distance of the mine from the power station, and due to logistical solution such as belts, trucks or trains.

To give some substance to this explanation, consider the following situation. Let us assume that the average cost is R290 per ton of coal supplied to the power station, the annual coal supply is 14.6 Mt and the power station capacity is 4 800 MW. The power station normally consumes 55 000 tons of coal per day. The normal practice for mining operations is to work a six-day week. Therefore, the mine will have to produce approximately 70 000 tons per day on average to ensure there is enough material for the power station to operate seven days a week and to build seasonal stockpiles.

If spontaneous combustion occurs in the bunker and burns out of control, destroying the associated equipment at the bunker, the worst-case scenario would be that it could take anything from a week to six months to repair, assuming that the bunker's civil structure is still intact. In this scenario, the revenue cost to the mine would be approximately R2,923 billion (70 000 x 6 days x 24 weeks x R290/ton).

The power station can continue to operate for 22–27 days on its backup stockpiles. With depleted stockpiles, other mines will have to provide the coal needed. If this fails, the power station will finally cease operation. This does not take into consideration the impact on the power station's future and the power grid stability. At the time of writing this document, South Africa was experiencing serious problems with power shortages.

Due to the magnitude of the problem of spontaneous combustion in coal bunkers, further investigation is necessary. The aim is to find a solution to prevent and control spontaneous combustion in storage bunkers. The outcome will provide design engineers with a guide and a decision analyser to be used for checking the coal being stored, the mining practice and the physical factors around the bunker. Recommendations will be made on the bunker design and

management control techniques. Management of spontaneous combustion is a legal requirement by the Department of Minerals and Energy (DMR).

## 1.3    PROBLEM STATEMENT

A critical investigation into spontaneous combustion in coal storage bunkers is needed. The purpose is to compile a quick design guide and a decision analyser for engineers designing or working with coal storage bunkers.

## 1.4    OBJECTIVES

The main objectives of the study are as follows:

1.  To review the different areas where spontaneous combustion is prevalent in coal mines. This will provide an understanding of the work done previously by other researchers.
2.  To evaluate what causes spontaneous combustion in coal stockpiles, dumps and bunkers or silos. This part of the work will elucidate the causes of spontaneous combustion and the latest developments in this field.
3.  To evaluate what preventative measures are available to prevent spontaneous combustion. This part of the investigation will establish what work has been done by other mines to prevent spontaneous combustion.
4.  To provide an understanding of the affected operational envelope or limits in order to address the problem.
5.  To establish guidelines for preventing spontaneous combustion in raw coal storage bunkers, i.e. to provide, as far as possible, a solution to the problem.

## 1.5    METHODOLOGY

The following methodology was used to address the objectives set:

- *To review the different areas where spontaneous combustion is prevalent in coal mine*. An evaluation of what causes spontaneous combustion in coal stockpiles, dumps and bunkers or silos was done by means of a detailed literature survey of previous research. A further aim was to review the latest developments in this field.

- *To evaluate what preventative measures are available to prevent spontaneous combustion.* The aim was to establish what other mines have done or are doing to prevent spontaneous combustion. Various experts in the field were consulted to give their inputs and share their experience and challenges.

- *To understand the affected operational envelope or limits.* An investigation was carried out to understand the origin of the problem and to map out the operational limits. This was done by using qualitative measuring techniques and by evaluating actual mine data obtained from field research.

- *To understand the causes of spontaneous combustion in coal bunkers.* Different measuring techniques were used to evaluate the problem within the operational context, such as thermographic imaging and velocity metering, together with an understanding of the coal characteristics. Relevant data were collected and an analysis was performed.

- *To establish a guide and decision analyser for preventing spontaneous combustion in raw coal storage bunkers and to arrive at a solution to the problem.* All relevant information was reviewed and objectively documented as guidelines by categorising the data into three areas:
    - The type of coal being supplied to the bunker
    - The mining practice
    - The physical factors around the bunker

## 1.6    SCOPE OF THE STUDY

The study focused on preventing spontaneous combustion in raw coal bunkers on surface. The major portion of the work was dedicated to this problem.

In coal mining spontaneous combustion can occur in many areas such as stockpiles, underground workings, waste dumps, coal faces, in-pit ramps and backfill areas. Although all these areas were reviewed and evaluated, the study did not cover the following: underground workings, waste dumps, stockpiles (ROM, waste and product), coal faces, in-pit ramps and backfill areas.

## 1.7   STUDY OUTLINE

This dissertation report is composed of seven chapters:

**Chapter 1:** Introduces and gives the background to this report. Presents the problem statement, clarifies the objectives, defines the scope of the study and outlines the methodology.

**Chapter 2:** Introduces and discusses the existing literature on the topic of spontaneous combustion.

**Chapter 3:** Relays the results stemming from the knowledge gained in the literature review, the field research and the interview feedback.

**Chapter 4:** Analyses and evaluates the results of the study. This is discussed in relation to the research outcomes.

**Chapter 5:** Presents the conclusions.

**Chapter 6:** Makes recommendations in terms of the bunker design and management control techniques to be considered or used by design engineers for bunkers and silos.

**Chapter 7:** Gives suggestions for further work.

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# CHAPTER 2
# LITERATURE SURVEY

## 2.1    INTRODUCTION

One of the most significant hazards to the safety of workers in a coal mine is spontaneous combustion (SC). This phenomenon has an enormous environmental impact and affects the quality of life for future generations.

In South Africa (SA), many cases of SC have occurred in underground coalmines, surface dumps, shallow workings in the vicinity of Witbank and in ships carrying export coal. It is a huge concern in the country's coal industry and, in particular, surface coal mines. It occurs when surface mines extract seams previously partially mined by underground bord-and-pillar operations. Once exposed to the air, pillars that were left from previous mining operations start to burn after a few days. Special prevention methods and control techniques are required to control this. It is important to manage the possibility of SC because if it occurs, it will lead to an increase in temperatures (high heating), aiding ignition and resulting in the promotion of a fire.

Fires in coalmines are a major problem worldwide and have been a great concern for both the industry and researchers in this field. The majority of fires that occur in different coalfields around the world are mainly due to SC. It is not only dangerous to mine employees, but it also results in the loss of valuable coal, which is the primary source of energy in SA. It disrupts mining operations and therefore a detailed understanding of the problems associated with SC is necessary.

Inadequate evaluation, measurement and control of increased temperatures within an exposed bench, stockpile or in a bunker, combined with air enrichment of the encompassing environment, may lead to unwanted events. There are a number of methods for preventing, detecting, monitoring, controlling and managing SC in mining operations, which will be discussed in detail in this chapter.

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### 2.1.1 Need for the study

This introduction provides an overview of what SC entails and its effects on South African coalmines because this is a real and serious problem affecting these mines. The decision was made to focus on SC in coal storage bunkers specifically. In order to address the purpose of the investigation, a holistic approach to the topic of SC was taken and is documented accordingly in this chapter. Some of the information relates directly to SC in bunkers, but other problem areas are included to support a detailed understanding of SC.

## 2.2 SELF-IGNITION OF COAL

Self-ignition is combustion by heat released and generated through chemical or biological reactions without an external ignition source. The sequence of self-ignition is as follows:

- Initially the material must exhibit thermal properties relating to self-heating
- This increase must reach a critical condition (a high temperature must be reached rapidly).
- A sustained smouldering starts.
- The smouldering bursts into flames when exposed to an increased air supply reaching the outer surface of the area where it started.

This is a basic explanation of how coal could self-ignite in a coal storage bunker.

## 2.3 SPONTANEOUS COMBUSTION

### 2.3.1 What is spontaneous combustion (SC)?

SC is an oxidation reaction that occurs without an external heat source. It is not limited to coal and does occur in other materials as well (Phillips, Uludag & Chabedi 2011). Basically, SC is the process whereby heat is generated spontaneously within an oxidised substance and where the dissipation of heat to the environment is prevented.

Under these conditions, the temperature of the reacting material rises, which leads to an increase in the rate of reaction and greater heat generation (Adamski 2003). The accumulation of heat can lead to ignition of the reactant. For combustion to occur, three basic elements are

required: oxygen, fuel and heat, as indicated in Figure 2.3. If any one of these elements is absent, it will result in the temperature cessation of burning (Phillips *et al.* 2011).
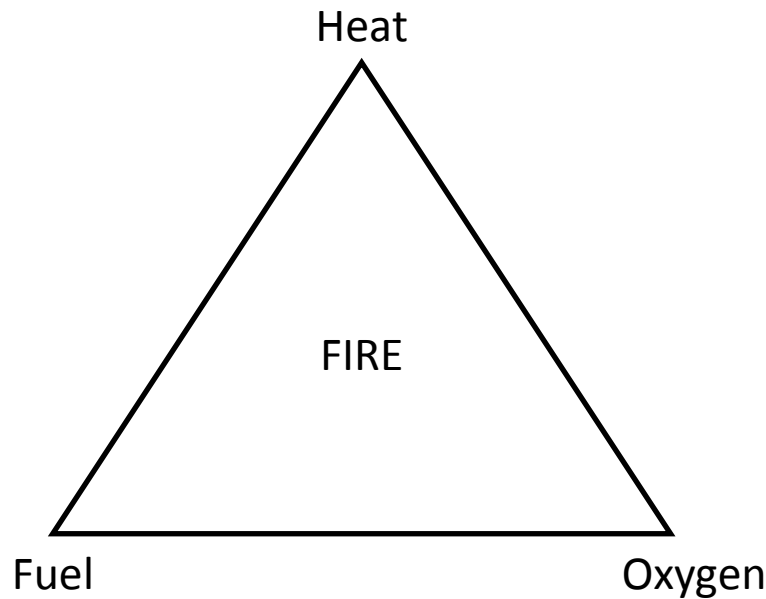


**Figure 2.3: The fire triangle (Chitty & Fraser-Mitchell 2003)**

Some of the notable toxic gases produced by SC are sulphur dioxide [$SO_2$], nitrogen oxides [$NO_x$], hydrogen sulphide [$H_2S$], methane [$CH_4$] and carbon monoxide [CO] (Phillips *et al.* 2011).

The explosion of coal dumps can be attributed to the concentration of flammable gases such as $H_2$, $CH_4$, $H_2S$ and CO. The right concentration of the gases with the right amount of oxygen and heat results in the explosion of these mixtures (Adamski 2003).

In SA, SC occurs during the storage of coal in bunkers, silos, hoppers and open-air stockpiles, or in backfilled waste heaps. Coal is stored for different reasons, namely to provide a buffer between operations, to blend coals and for quality control purposes. Storage bins between plant sections ensure that each section receives the required rate of coal. Product coal is stockpiled before loading onto trains to ensure that correct tonnage of coal is available. Coal is stockpiled at Richards Bay Coal Terminal (RBCT) to control rail and shipping requirements. SC does occur at RBCT and when it occurs or is detected, the procedure is to cool down the hot coal by dozing the coal apart and using water to spray cool the coal (Bezuidenhout 2016). This method

of cooling the coal can only be applied at the mine bunker once the coal has been safely emptied from the bunker.

A large proportion of raw coal requires beneficiation in order to improve its quality for utilisation in power generation, metallurgical applications and other industrial processes. All the coal exported through Richard's Bay and other ports is beneficiated. An unfortunate consequence of coal processing is the fact that large tonnages of discard coal arise and have to be disposed of. The usual practice in SA is to dispose of this coal on discard dumps (Falcon 2014).

A detailed description of SC is provided below so that the concept is shown to be well understood before the topic is narrowed down to the purpose of this study. It is relevant to understand the different elements (oxygen, heat and fuel) and how each of them contributes to SC. The explanation of the different toxic gases is also relevant to understand the risk of exposure to employees and will be used in creating the guidelines. An understanding of the storage of coal is important to identify where this type of risk exists and how the problem could be solved in these areas.

## 2.4 FACTORS AFFECTING SPONTANEOUS COMBUSTION

According to the Phillips *et al.* (2011), the earliest classification of the factors affecting SC was compiled in 1928 by Davis and Reynolds. These factors are grouped into chemical and physical properties as set out below. Table 2.4 indicates the chemical and physical factors specific to SC in the coal bunker.

The chemical factors are:
- presence of pyrites
- rank of coal
- weathering
- moisture
- organic sulphur
- chemical deterrents (calcium chloride and sodium bicarbonate)
- bacteria

- particle size
- moisture

The physical factors are:
- oxygen supply
- temperature
- occluded gases
- ventilation
- conductivity
- ozone

**Table 2.4: Parameters specific to coal bunker SC**

| Chemical factors | Physical factors |
|---|---|
| Presence of pyrites | Oxygen supply |
| Rank of coal | Temperature |
| Weathering | Ventilation |
| Organic sulphur | Standing time of coal |
| Particle size | Inadequate loading of coal |
| Marceral composition | Poor cleaning techniques |
| | Bunker design (hot spots) |

Various researchers on this topic have drawn similar conclusions in terms of the salient factors affecting SC. In particular, Kaymakci and Didari (2002) explain how physical and chemical factors play a role in SC. They state that the following factors are involved in producing conditions favourable to an SC event:

- The pyrite content may accelerate SC.
- Changes in the moisture content, i.e. the drying and wetting of coal, apparently have an influence on the propensity of coal to self-heat.
- It is widely recognised in the coal industry that lower ranking coals are more susceptible to SC than higher ranking coals.
- Particle size has an inverse relationship to SC in a coal: the smaller the particle size, the greater the surface area that is available on which oxidation can take place.

- The ash content decreases the propensity of coal to heat spontaneously. However, certain constituents of the ash may lead to the acceleration of heat (lime, soda and iron compounds), whereas other constituents (alumina and silica) could have a retarding effect. Therefore some components of ash promote combustion while others inhibit its development.

- Faulting and faulted zones could also contribute to the dangers of SC by allowing air ingress into the coal mass.

- The rank of a coal is the most important factor: as the rank decreases towards lignite, the tendency for coal to self-heat increases, i.e. the lowest ranked coal is more likely to self-heat under the same set of conditions. The type of coal being mined is therefore important. An example of this is the coal being mined at GG which is bituminous coal, ranked second lowest next to lignite. The highest ranked coal, anthracite, is least likely or has the least tendency to self-heat. The rank, combined with the inherent reactivity of the coal's particle size, results in an overall oxidation reactivity for the coal which could be regarded as or termed the "pile oxidation reactivity" (Adamski 2003).

It is necessary to determine which of the above-listed factors are relevant to the present investigation and which can be managed to prevent or control SC in the coal bunker. They will be considered and applied in the analysis and evaluation of results in Chapter 5.

## 2.5    OTHER FACTORS AFFECTING SPONTANEOUS COMBUSTION

SC can also occur in coal outcrops and in shallow workings exposed by subsidence, either directly or through fissures and tailings dams (Phillips *et al.* 2011).

Fires attributed to ignition by SC have resulted in the deaths of people as well as the loss of property. Other factors include:

- Explosions of methane due to ignition by SC, resulting in the loss of lives
- Pollution caused by gases liberated as a result of SC reactions, which have had major environmental impacts
- Oil shale bands and adjoining coal seams, which play an important role in mine fires
- Partial extraction in underground mining methods, notably where part of the coal seam is left in the goaf and in pillars, this can also contribute to the potential for SC

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- The airflow rate providing oxygen while dissipating the heat produced (Adamski 2003)

Although the above information may not be relevant to the purpose of this investigation, or used in it, it has been included to indicate that there are other factors that affect SC.

## 2.6    THE EFFECTS OF SPONTANEOUS COMBUSTION

In the 1960s, continuous problems relating to SC resulted in renewed interest in the early detection of increased thermal conditions.

Fires are likely to occur in an underground coal mine when coal spontaneously combusts, which could lead to serious consequences. The following examples are indicative of the serious effect SC has had in coal mines:

1. In 1994, an underground coal mine in Queensland, Australia (the Moura No. 2 Mine), experienced two underground explosions which resulted in the death of 11 people and the ventilation fan being destroyed. An inquiry into this incident revealed that the explosion was caused by a failure to acknowledge and effectively treat the prevailing conditions leading to the self-heating of coal which resulted in SC. A number of systems were in place to detect SC and regular inspections were done to detect unsafe conditions. Tucker (2000) used this incident as a case study to examine the underlying reasons why workers were exposed to such dangerous conditions and the lessons learned.

2. In August 1956, in the town of Marcinelle, at the Charleroi coalfield of Belgium, 262 miners lost their lives underground as a result of the outbreak of a fire in the Bois deCazier mine. Subsequently, a Coal Mining Safety Conference of the European Coal and Steel Community took place on 6 September 1956. The purpose of this conference was to review safety regulations and to establish effective safety measures (Marcinelle 1956)

3. In India, a fire disaster at the New Kenda Mine in Raniganj coalfield claimed 55 lives (Vijay & Singh 2013)

It can be deduced from the above cases that SC in underground coal mines is a serious hazard if left undetected and uncontrolled. The cases illustrate the fact that SC is not just a domestic problem, but also presents a serious problem globally. A comparative analysis on the global problem would be of great interest, although it does not form part of this study.

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## 2.7    RISK AND DANGERS OF SPONTANEOUS COMBUSTION

Small-scale fires in stockpiles or areas exposed by mining may be extinguished or controlled by flooding the area with water, or by removing the burning material. However, caution must be exercised when combating SC fires with water because a dangerous reaction between the water and the heated coal could occur (Phillips *et al.* 2011).

It is possible to produce water gas to control heating. The Webster Comprehensive Dictionary defines *water gas* as "a highly poisonous mixture of carbon monoxide (CO) and hydrogen ($H_2$) produced by forcing steam over white hot carbon such as coal or coke". Both these gases are extremely flammable and when produced in the reaction between hot carbon and water, the chemical reaction is $C+H_2O= CO+H_2$. It is important to note that water gas has wide explosive limits (4 to 74%) which relate to the highly toxic nature of carbon monoxide in the presence of a source of ignition. Therefore, water gas should be avoided as much as possible. The amount of water gas produced should be limited and must exclude air (Phillips *et al.* 2011).

In surface operations, the risk of explosion is lower. However, crews fighting SC on a vessel (ship) by using water should monitor carbon monoxide and hydrogen levels.

A widely accepted method is for the material to be spread out to cool and the ash disposed of in a manner suited to its chemical and physical properties. Protective clothing and breathing apparatus should be provided and equipment must be suitable for the particular work. For example, no rubber tyres or petrol-driven equipment should be used (Phillips *et al.* 2011).

The specific risks and dangers of SC applicable to the findings of this study must be identified. In particular, the risk of a water gas explosion will be considered when making recommendations for management controls on a mine.

## 2.8    ASSESSING POTENTIAL SPONTANEOUS COMBUSTION

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## 2.8.1    Prediction, detection and control

There are a number of methods for predicting, detecting, monitoring, controlling and managing SC in mining operations, some of which are discussed below.

### *Prediction of the SC risk*

According to Phillips *et al.*(2011), the classification of coal type (discussed in Section 2.4 above) is required for prediction. The following techniques are available to measure the inherent characteristics of a coal used to predict its behaviour:

An examination of the chemical constituents, namely:

- rank
- petrographic classification
- moisture
- volatiles
- oxygen
- sulphur content

Thermal studies, such as:

- initial temperature
- crossing point temperature
- crossing and ignition point
- modified crossing point temperature
- differential thermal analysis(DTA)
- adiabatic calorimetry
- R70 (Humphreys 2004)

Examination of the extrinsic characteristics by means of:

- risk mapping
- risk indexing

The prediction of SC can be done at the mine design stages, i.e. during the planning of a new mine. The ventilation system is important as its design for a long wall face will be based on the requirements to control methane in the goaf. The gas content of the seam can be quantified and gas levels in goaf areas can be modelled for different ventilation systems.

### *Detecting SC*

One of the principal means of detecting SC is the monitoring of carbon monoxide concentration using a gas monitoring system.

Conditions conducive to SC can be detected before any obvious smoke or flame is noted. According to Phillips *et al.*(2011), the following factors can assist in early detection:

- Temperature difference, heat haze and steam plumes may be observed on cold mornings and during periods of high humidity. Hotspots may also be detected by infrared monitoring devices or photography.

- Routine surveying of stockpiles using infrared scanning devices is an excellent precaution. This technology is also applicable to the detection of heating in the highwall but is not routinely practised on mines as it may yield negative results for years before heating is detected.

- Efflorescence caused by the decomposition of pyrites and the sublimation of sulphur is a strong indication of heating in pyrite (high-sulphur) coals.

- Infrared cameras can be useful in detecting near-surface heating.

- "Smell-mine fires" are readily recognisable by their distinctive smell. Oxidation of the coal causes the release of large volumes of noxious and flammable gases, which in themselves may represent hazards, such as asphyxiation, poisoning, fires, carbon monoxide concentrations in enclosed places and the risk of explosions.

The prevention of SC is imperative, especially in an underground coal mine, where, if not detected and prevented, it could have catastrophic consequences, such as the Moura No.2 Mine Disaster, mentioned earlier in Section 2.6.

This section has demonstrated how urgent the need is to prevent SC, which substantiates the reason for the current investigation. The information on the classification of coal, more specifically how to classify a coal based on its properties, is used in this investigation. The

classification of coal is important because once the chemical constituents are identified, the reaction of the coal can be predicted, which can be used in providing guidelines for the design of coal storage bunkers.

## 2.9   TECHNIQUES AND METHODS FOR ASSESSING THE RISK OF SPONTANEOUS COMBUSTION

The current methods and techniques for assessing the potential for SC that could occur in an underground coal mine are qualitative and subjective. Humphreys (2004) discussed two types of tests in his paper, namely the R70 or Adiabatic Self-heating Test and the Relative Ignition Temperature (RIT) or Crossing Point Test. The R70 developed by Humphreys has become the standard method used to rank the SC potential of Australian coals.

### 2.9.1   The R70 or Adiabatic Self-heating Test

The R70 test as shown in Figure 2.9a is used in the laboratory to simulate conditions that lead to SC in the field. A 130 g sample of coal is crushed and dried under nitrogen to prevent oxidation. The sample is loaded into a 250 ml vacuum flask which is connected to a gas supply and mounted in a temperature-controlled oven. A thermocouple is placed in the centre of the coal to measure its temperature. Nitrogen gas is used as a carrier to prevent pre-oxidation and the temperature is controlled at 40 ºC. When the coal temperature stabilises to that of the oven temperature, the gas supply is changed to oxygen and the temperature control is changed to adiabatic mode. During the oxidation phase of the test, heat losses from the coal are minimised by a number of factors: the combination of the vacuum flask as a reaction vessel, preheating of the gas supply to equal the oven temperature and then allowing adiabatic temperature control. If the coal is left unchecked, the temperature would continue to rise to the point of ignition. This is, however, prevented because the test is stopped before the temperature is significantly high (Humphreys 2004).
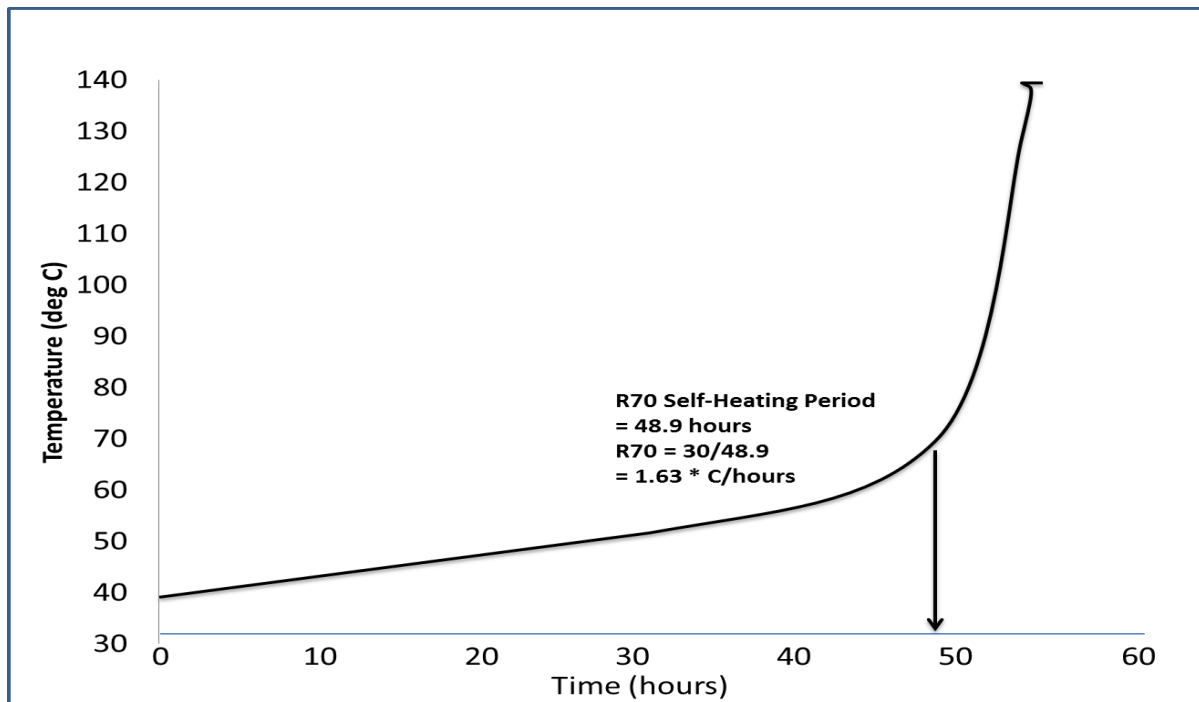
**Figure 2.9a: Typical R70 test result (Humphreys 2004)**

Once the coal temperature exceeds 70 $^{\circ}$C, the rate of self-heating increases rapidly and the coal ignites if the test is not stopped. The average rate of self-heating is calculated in degrees Celsius per hour from 40 to 70 $^{\circ}$C. Therefore, the test is referred to as the R70. Values for the R70 range from 0 $^{\circ}$C per hour (coals which do not self-heat in the apparatus) to about 8 $^{\circ}$C per hour in certain cases. The results are generally in the region of 0.25 to 2 $^{\circ}$C.

The conclusion drawn from the R70 test was that the propensity for SC as measured by this test is related to coal rank as measured by fixed carbon content or oxygen content, with a lesser influence noted due to vitrinite content. The R70 values above 1 $^{\circ}$C per hour were indicative of coal prone to SC. Values between 0.5 and 1 $^{\circ}$C per hour indicated moderate propensity and less than 0.5 $^{\circ}$C per hour indicated low propensity for SC (Humphreys 2004).

## 2.9.2 United States Bureau of Mines (USBM) Minimum Self-heating Temperature test

The USBM Self-heating Temperature test uses an apparatus akin to the R70 Adiabatic Self-heating Test but the USBM test is conducted and assessed differently. A small sample of crushed coal is initially dried in nitrogen at 67 $^{\circ}$C and then placed into a small thermally

insulated reaction vessel. It is then heated and exposed to a flow of nitrogen to prevent prior oxidation. At stabilisation of the initial temperature, the gas flow is changed to humidified air until either self-heating occurs or the coal sample begins to cool. The minimum self-heating temperature is that initial temperature at which the coal will self-heat in the apparatus. This requires repeat tests at 5 $^{\circ}$C intervals for any particular coal until the transition between self-heating and non-self-heating behaviour is observed. The values for the minimum self-heating temperature have been reported to vary from 35 to 135 $^{\circ}$C. Coals with a minimum self-heating temperature of less than 70 $^{\circ}$C are more likely to have the potential to self-combust (Smith, Miron & Lazzara 1988)

### 2.9.3    Relative Ignition Temperature (RIT) or Crossing Point Test (CPT)

The RIT test is used extensively in Australia. A small sample of freshly crushed and screened coal is placed into a small temperature-controlled furnace. The temperatures of the coal and the surrounding furnace are each measured by a thermocouple and recorded throughout the test. In the beginning, the furnace temperature is maintained at 70 $^{\circ}$C as carbon dioxide flows through the coal sample to prevent pre-oxidation. When the coal temperature stabilises at 70 $^{\circ}$C, the furnace temperature is increased by 2 $^{\circ}$C per minute and the gas flow through the coal is changed to oxygen at 200 ml per minute. Due to the increased furnace temperature and the exothermic oxidation of the coal, the coal temperature increases. However, there is some lag between the coal temperature and the furnace temperature. As the rate of oxidation increases, the coal temperature eventually exceeds the furnace temperature. The temperature at which they cross is being referred to as the "crossing point temperature". An example of a test result is shown in Figure 2.9b.

The RIT test involves greater simplification of the SC process than the R70 test. It is based on the untried assumption that SC is related to oxidation rates, which control the SC behaviour of coal. SC in coal mines does not start at 70 $^{\circ}$C. Therefore the unstated assumption is that the rate of oxidation above 70 $^{\circ}$C is related to the rate of oxidation at lower temperatures. This test does not provide quantitative data on the SC characteristics of coal (Humphreys 2004).
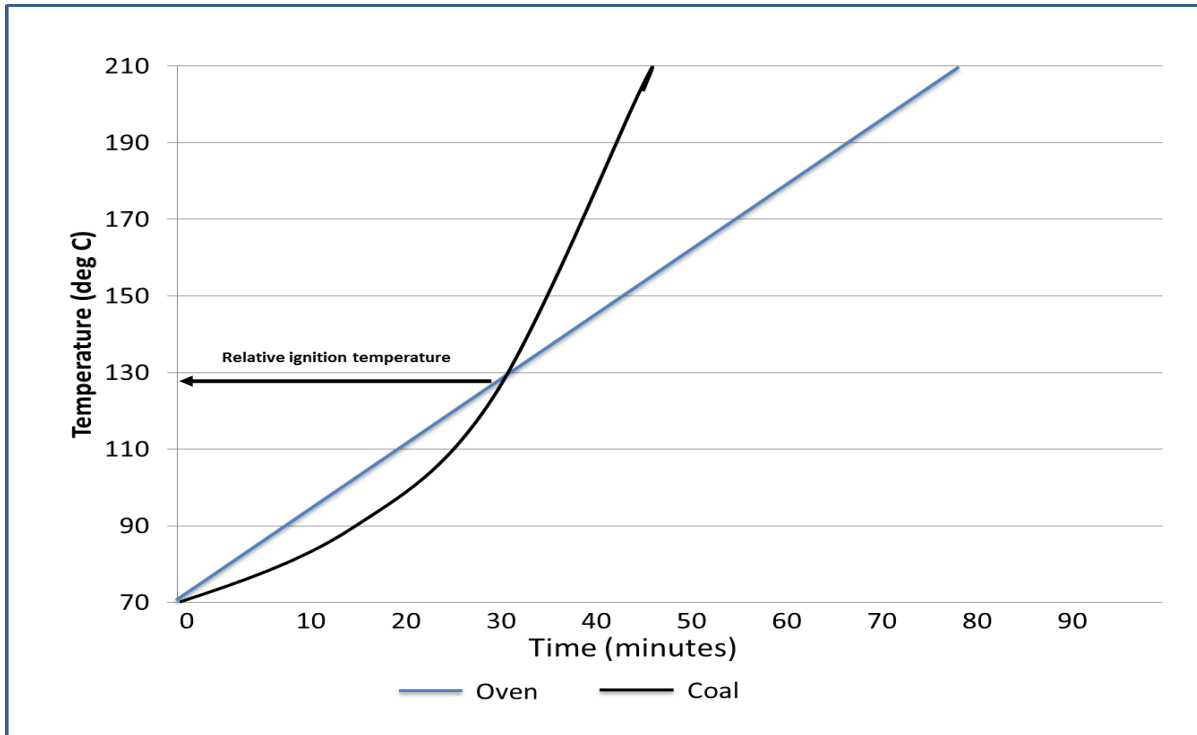
**Figure2.9b: Typical Relative Ignition Temperature test results (Humphreys 2004)**

## 2.9.4    Sealed Flask Test

The Sealed Flask Test was developed by the USBM. A 50g sample of ground, sieved and dried coal is sealed in a 500 ml Erlenmeyer flask. A miniature pressure transducer is fitted to the flask and pressure readings are taken at regular intervals for 7 days. The internal flask pressure begins to drop as soon as the coal is sealed in the flask. The change in pressure ($\Delta$) over 7 days, referred to as $\Delta p7$, is taken to be indicative of the potential for SC. Analysis of the gas samples from the flask revealed that significant proportions of oxygen were absorbed by the coal. There was some correlation, with lower rank coals showing higher $\Delta p7$ values which represented a greater potential for SC. The relative SC potential is considered to be high when $\Delta p7$ is greater than 114 mmHg and is considered to be low when $\Delta p7$ is less than 56 mmHg.

This test is based on the premise that the oxygen in the flask is absorbed by the coal in the same way that oxidation reactions cause SC. The parameter $\Delta p7$ is a measure of the rate of absorption and therefore a measure of the potential for SC (Humphreys 2004).

## 2.9.5    Large-scale testing

Large-scale testing has been used to study SC in coal stockpiles. For example, a stockpile of 800 tons of 50 mm coal is known to combust spontaneously on the surface from an initial temperature of 25 °C (Humphreys 2004).

## 2.9.6 Thermogravimetry (TG)

Using thermogravimetry, the weight of the samples is measured as a function of temperature, as shown in Figure 2.9c. The first differential equation of the TG curve defines the amount of heat absorbed during differential thermal analysis (DTA) (Fan & Dong 2011).
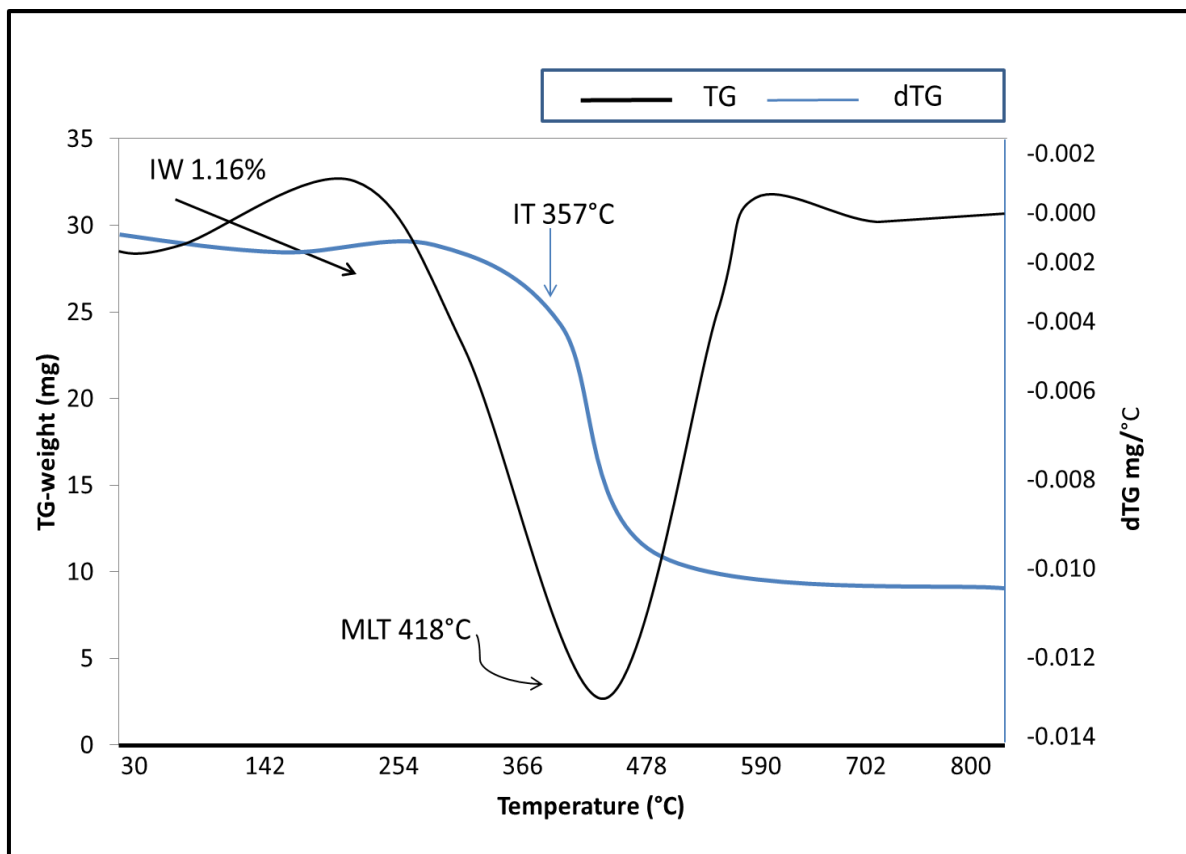


**Figure 2.9c: Thermogravimetry results (Fan & Dong 2011)**

## 2.9.7 Differential Scanning Calorimetry (DSC)

For DSC, the sample is placed in a crucible and heated at a previously established regular rate. The difference in temperature between the sample and a reference sample is measured and recorded against the temperature of the oven so that the exchanges of heat in the sample may be determined (Fan & Dong 2011).

## 2.9.8    Wire Mesh Cube Test

In this test wire basket cubes of various sizes are used together with an isothermal oven which reproduces environmental temperatures. A sample is held in the oven at a fixed temperature and the evolution in the sample temperature is observed over a period of time. Three different behaviours can be observed, as shown in Figure 2.9d.
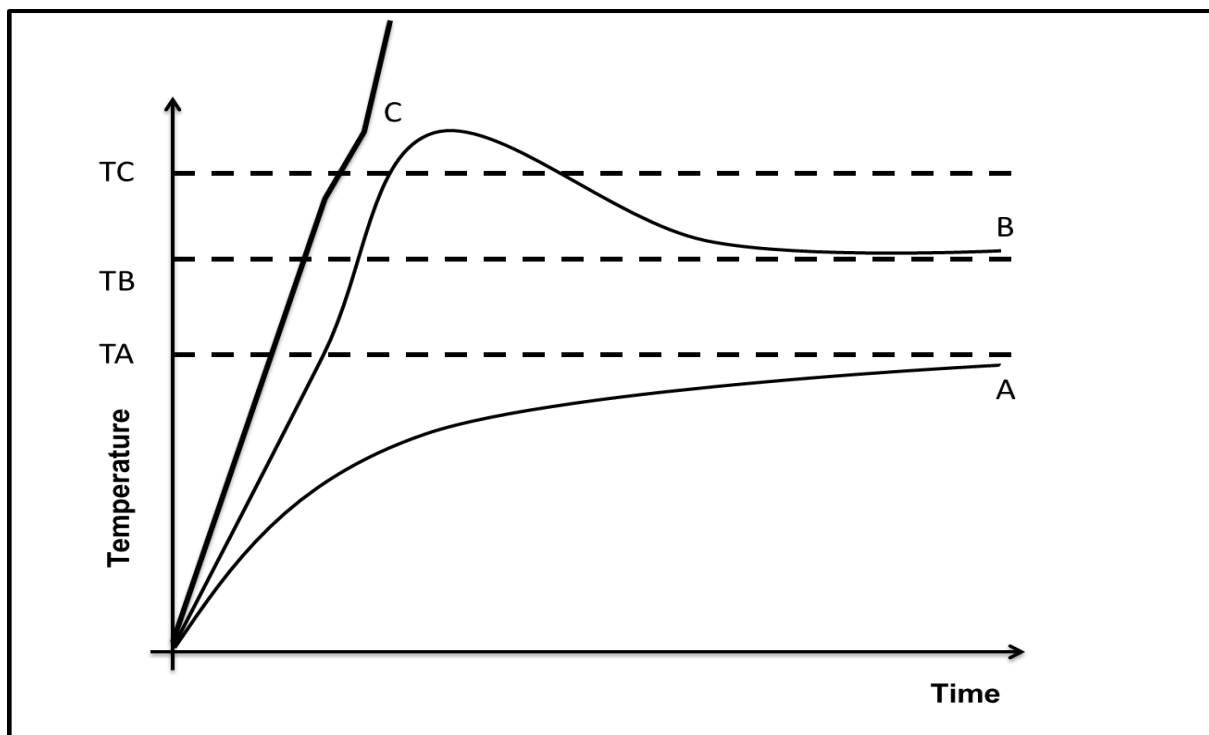


**Figure 2.9d: Thermal behaviours (subcritical, critical and supercritical) (Fan & Dong 2011)**

Curve A shows the sample temperature approaching the oven temperature, although it is always lower. The sample itself does not produce the heat, and no ignition is observed.

Curve B shows the sample temperature exceeding the oven temperature for a while and then declining and trending with the oven temperature.

Curve C shows the sample temperature exceeding the oven temperature rapidly and never dropping. Ignition is obtained. The temperature of the oven is increased in steps of 5 K until the supercritical condition occurs. The temperature of self-ignition is the mean between the last critical and the first supercritical temperatures. The test is repeated for samples of different volume (Fan & Dong 2011).

The Frank-Kamenetskii theory of thermal ignition, first proposed in 1939, considers temperature gradients within the self-heating body and provides better agreement with experiments for solid bodies with low thermal conductivity. The assumptions of this theory are:

- The temperature within the self-heating body varies spatially.
- The heat generation is assumed to be due to a single chemical reaction of a simple integral order.
- Both the heat of reaction and the activation energy are assumed to be sufficiently large to support ignition behaviour (Fan & Dong 2011)

The TG and DSC thermal analysis methods are used to obtain relevant information, especially when material of unknown origin and composition is involved. According to Fan and Dong (2011), the Wire Mesh Cube Test is more reliable than the common thermal analysis method because the influence of volume is considered. However, the Wire Mesh Cube Test has a limitation: due to the relatively small sample sizes involved, critical temperatures are normally above 100 $^{\circ}$C, whereas the real situation may involve normal ambient temperatures of about 20 $^{\circ}$C. This means that if the substance has a moisture component, the oven tests will be run with the specimen fully desiccated. In a real situation, moisture movements may play a major role.

The mathematical formulation used in Figure 2.9d can provide the dimensions of storage leading to ignition and the time required to reach ignition conditions. It would therefore appear that this formulation is reliable. According to Adamski (2003), the self-heating process is as follows: when the coal temperature begins to rise above ambient temperature plus $\pm$ 65–150 $^{\circ}$

C, the coal begins to give off measurable quantities of gas aerosols, hydrogen, CO and $CO_2$, which are precursors of combustion. As the temperature increases further too about 315–370 °C, large particles are emitted.

### 2.9.10    Use of the tests in this study

Information from the different tests used to assess SC will be extrapolated and used for the current investigation. The tests will be critically reviewed to see which ones are relevant. The results from some the tests described above indicate the possible safe duration of storage which is very important for the guidelines that will be developed.

According to Beamish and Blazak (2005), the SC propensity of coal can be obtained for the R70 values (1) and CPT values (2) using the exploration drilling samples with the following equations (1) and (2). This information was used on the GG borehole information and is presented in Table 2.9.10.

R70 = 0.0029*ash2-0.4889*ash+20.644-------------------------------------------(1)
CPT = 170-5.16*M-2.18*A-0.005*M2+0.28*M*A+0.02*A2-----------------(2)

**Table 2.9.10: Spontaneous combustion propensity results of the GG coal**

| Bench | Borehole depth | Ash | CV | Moisture | Sulphur | Volatile | R 70 | CPT |
|---|---|---|---|---|---|---|---|---|
| | m | % | MJ/kg | % | % | % | (°C/h) | (°C) |
| Bench 2 | 16-29 | 50.14 | 14.38 | 2.18 | 1.40 | 21.59 | 3.42 | 99.22 |
| Bench 3 | 29-45 | 54.01 | 12.86 | 1.58 | 1.03 | 19.73 | 2.70 | 92.84 |
| Bench 4 | 45-62 | 54.46 | 12.39 | 1.56 | 1.08 | 19.79 | 2.62 | 92.56 |
| Bench 5 | 63-79 | 55.40 | 12.50 | 1.74 | 0.74 | 18.41 | 2.46 | 94.26 |
| Bench 6 | 80-83 | 34.58 | 20.53 | 1.51 | 1.51 | 23.45 | 7.21 | 103.91 |
| Bench 7B | 89-90 | 43.35 | 17.25 | 1.55 | 2.18 | 19.41 | 4.90 | 97.01 |
| Bench 9A | 94-102 | 31.39 | 21.55 | 1.64 | 2.36 | 19.64 | 8.15 | 107.75 |
| Bench 9B | 94-102 | 21.77 | 25.15 | 1.67 | 2.05 | 22.12 | 11.38 | 120.07 |
| Bench 11 | 106-111 | 22.44 | 24.96 | 1.61 | 1.83 | 22.41 | 11.13 | 119.03 |
| Bench 13 | 124-126 | 19.87 | 25.96 | 1.76 | 1.63 | 21.68 | 12.07 | 122.96 |

Table 2.9.10 shows the R70 and CPT values of the coal in the different benches. These values indicate the propensity of coal to SC. This coal is being transported to the bunker. Benches 2, 3, 4, 5 and 7B are sent to the bunker compartment to feed plant GG8 as per Figure 1.1c. This coal, in combination, has an average value of 18.3 hours' standing time before it will spontaneously combust. If Bench 7B material is removed from the bunker feed, this will improve to around 20.5 hours' standing time. Benches 6, 9A and 9B are sent to the bunker compartment to feed plant GG7 as per Figure 1.1d. This coal, in combination, has an average value of 8.17 hours' standing time before it will spontaneously combust.

## 2.10    THE IMPACT OF SPONTANEOUS COMBUSTION INTERNATIONALLY

### 2.10.1    International literature on SC incidents at mines

Major coal fires around the world have occurred in the Xinjiang coalfield in northern China, the Rujigou coalfield in the Nirgxia region of China, Pennsylvania coal fires in the USA and the Jharia coalfield in Bihar, India (Stracher & Taylor 2004).

*China*

SC of coal is a major hazard encountered in the coal mines of China. A paper by Wan-Xing, Zeng-Hui & De-ming (2011) presents detailed information on this problem and is reviewed here.

SC of coal in high caving regions is like an internal fire in the particular environment of underground coal mines. The appearance of caving in the tunnel is the first indication, while the fire is sheltered by supports. SC is considered to be more dangerous than any other type of fire because it is concealed. Coal fires are generally very difficult to put out. Technologies to prevent mine fires have been developed and applied internationally. These technologies include water and grouting injection, gelatum infusion, inert gas injection and so forth. However, traditional technologies have limitations in preventing fires in the high caving region. For example, gelatum, which consists of sodium silicate and ammonium salt, emits ammonia, a toxic gas. High-molecular-weight gelatum and foamed resin are expensive. Inert gases are prone to diffusion with airflow. Water and grouting injection easily flow away along the cracks of the tunnel roof. Moreover, none of these methods can efficiently prevent SC in the tunnel

fall of ground. The formation of this region depends on the geological structure and quality of the tunnel construction.

The tunnels of fully mechanised top-coal caving workings are normally excavated along the seam floor, which leaves thick coal at the top of the tunnels. After tunnel construction, the original balance of formation pressure is destroyed in a certain segment of the roadway because of stress concentration. The tunnel fall of ground, where tunnel caves are prone to occur, is characterised by particularly strong ground pressure, which results in local pressure concentration. There are three regions which consist of cracked, separation and fault subsidence areas. In the first region, the coal is completely cracked and the stress is fully released in the cracked area which produces approximately 2 to 3 m of float coal with a natural accumulation state. The air in the tunnel can easily come into contact with the loose coal through fissures in this region which will facilitate an oxidation reaction. Cracked coal is exposed to air when the tunnel caving forms. The continuous oxygen supply is a determining factor for SC of coal. Based on the oxygen supply method for the float coal in the tunnel fall of ground region, through analysis of the top-coal caving region in the intake airflow roadway of 12190 working face at the Geng Cun Coal Mine, two ways were found by which air leakage is produced, namely:

1. Hot wind pressure caused by the temperature difference between internal coal tunnels, and
2. Dynamic differential pressure generated by an undulating tunnel.

The authors (Wan-Xing *et al.* 2011) concluded that the hot wind pressure is related to the depth of caving and the temperature difference between the upper and lower parts of the tunnel cave fall of ground. The deeper the depth of caving, the greater the temperature difference and hot wind pressure, which can result in a great amount of air leakage. Hot wind pressure is also related to the temperature difference between the upper and lower parts of the tunnel cave fall of ground when the depth of caving is constant. At the same time, the longer the high caving exists, the more heat is accumulated, which brings about a strong hot wind pressure.

In their paper Wan-Xing *et al.* (2011) presented a new technology called the "three-phase foam" (discussed below) which was successfully used in the Geng Cun Coal Mine in the Henan Province of China. This technology was successful in extinguishing a serious mine fire that occurred in the high caving region of the tunnel. However, it must be mentioned that this

technology originated from an instruction to researchers at the China University of Mining and Technology to develop a plan for infusing three-phase foam to fight fires at the Geng Cun Mine.

In China, water mud slurry is injected into the cracks created by subsurface burning or into a series of holes drilled into underground shafts, drifts and slopes. The injection of this slurry smothers the flames. The surface is then covered with large amounts of soil to inhibit the entry of oxygen into the coal seams (Stracher & Taylor 2004).

- *Three-phase foam*

The three-phase foam can be applied for the prevention of SC. It is composed of non-combustible material (fly ash, yellow mud and so forth), inert gas (nitrogen) and water. The foaming agent is first added to the fly ash or yellow mud and then nitrogen gas is injected. The multi-phase medium is formed with particles of fly ash or yellow mud through physical, mechanical stirring by the foaming generator. This multi-phase medium is termed the three-phase medium. It presents the advantages of both grouting and inert gas foam in controlling fires. A large amount of three-phase foam forms after nitrogen is infused into the slurry which contains the foaming agent; the volume of the foam increases significantly. It can stack upon itself, which helps fill the fire area and cover the coal left in the goaf. The nitrogen contained in the foam can remain for a longer period in the fire area to extinguish a mine fire(Wan-Xing *et al.*2011).

### The USA

In the USA, problems relating to abandoned mines occur mostly in Pennsylvania. The fires in these areas are controlled by using the same slurry flushing and surface-sealing techniques as in China. Underground mine entrances have been sealed with brick, tiles, cement blocks or clay barriers to inhibit oxygen ingress and reduce the risk of explosions (Stracher & Taylor 2004).

According to the US Department of Energy (1994, through its Office of Health, Safety and Security), the following guidelines can be used for minimising the probability of a fire:
- The greater the inherent moisture content, the greater the heating tendency.
- The lower the ash-free calorific value, the greater the heating tendency.
- The higher the oxygen content in the coal, the greater the heating tendency.

- Sulphur content is a minor factor in the spontaneous heating of coal.
- The finer the top size of the coal, the greater the surface area exposed per unit of weight and the greater the oxidation potential.
- Segregation of the coal particle sizes is often a major cause of heating. Coarse size particles allow the ingress of air into the pile at one location and the reaction with the greater surface areas causes fires at another location. Coals with a large top size (> 100 mm) will segregate more during handling than coal with smaller top size (< 50 mm)
- The rate of reaction doubles in relation to an increase in temperature of 8 to 11 °C.
- Freshly mined coal has the greatest oxidising characteristics but hotspots may not be prevalent for the first 1 to 2 months.

### *India*

India is a major coal producer. Most fires have occurred in the Jharia coalfield and are ignited by the SC of coal. Prior to nationalisation, exploitation without fire prevention codes was responsible for the conditions that led to these fires. Techniques used to extinguish fires have included trenching and surface sealing. For subsurface fires, inert gas injection, sand/bentonite slurry flushing and surface-sealing techniques have been used (Stracher & Taylor 2004). The following inhibitors have been used to reduce the SC susceptibility of coals:

- Monovalents such as sodium chloride, potassium chloride and lithium chloride
- Bivalents such as magnesium chloride, zinc chloride, calcium chloride, magnesium sulphate, ferrous sulphate and magnesium phosphate
- Trivalents such as from a chloride and aluminium sulphate (Panigrahi, Udaybhanu, Yadav & Singh 2005)

Most of the inhibitors indicate an increase in the crossing point temperature, that is the temperature at which SC occurred, which showed an inhibition effect of 5 to 10%.

According to Panigrahi *et al.* (2005), there has been information to indicate that in mines where the time between the exposure of coal and the start of heating is short, water is available as a prevention measure for the interaction of coal with air until it is ready to be mined. In one mine, coal having a sulphur content of 0,5% started to burn within two weeks of exposure. To prevent SC, the mine used a 300-m-wide water barrier. The technique involved the flooding of a 300-m-long section of the open cuts with water to a height of about 1 m. The overburden was blasted

about 2 m above the coal, leaving stubs of overburden material intact to act as a barrier to contain the water within the section. The water prevented contact between the coal and air, and was only removed prior to the mining of the coal.

The most commonly discussed method in international literature involves the sealing of cracks. Cracks may be sealed with a mechanical spraying device using a fire-protective coating material. The characteristics of a typical fire-protective coating are:

- ease of application by spraying
- compatibility with coal
- good adherence properties to prevent it from being washed down by water/rain
- when applied over coal surface, the formation of a uniform, thin coat
- maximum resistance to air penetration
- good fire-resistance capability
- coating remains intact for a long time
- no cracks appearing in the coating material and no scaling from the coal surface during blasting of the coal face
- shelf life of more than one year of the coating material (Phillips *et al.* 2011)

According to Singh and Singh (2004), this sealing technique was used in India in an opencast coal mine with a typical bench height of 20 m. The system used 0.8 to 0.9 kg/m$^2$. The thickness of the coating resulted in two coatings of 0.9 mm thickness. It was reported that the coating remained intact despite heavy rains.

The significance of setting out the data on this subject with respect to China, the USA and India is that these countries have already conducted research into the specific occurrence of SC and the impact it has had on their coal mines. The information also highlights the different control methods used to stop fires and prevent SC. It is useful to see how other countries handle the issue of SC as it may be possible to tailor these techniques for inclusion in the guidelines for preventing SC in coal bunkers, which is the subject of the current investigation.

## 2.11    THE IMPACT OF SPONTANEOUS COMBUSTION IN SOUTH AFRICA

In SA, the biggest problem of SC occurs in surface mines. SC is rare in underground coal mines. It is mainly the Witbank and Sasolburg coalfields that experience SC, as well as surface mines in areas previously mined by bord-and-pillar methods. In the Waterberg coalfield, SC problems have occurred with discards and blasted material which had been exposed for more than a month (Phillips *et al.* 2011).

At the Springfield colliery in Mpumalanga, heating has led to underground fires. During 1992 and 1993, New Vaal colliery in the Free State also experienced fires caused by SC. In May 1993, the mine stopped all pre-splitting and buffered the fire-ravaged areas in underground workings. This slowed the fires and controlled them. The extent of the buffer was increased from an initial 20 m to about 120 m. The highwalls were clad with sand from the mine. These techniques proved to be successful in controlling SC and are a good example of buffering the blasted workings(Phillips *et al.* 2011).

Depending on the properties of the coal, heating of broken coal left in stockpiles in the cut or elsewhere on a mine can occur after a period of time.

### New Vaal Colliery

This mine is owned by Anglo Coal. It is situated south of Johannesburg on the Free State side of the Vaal River and mines the reserves of the old Maccauvlei Mine. Maccauvlei was established in 1898 on the Transvaal side of the river. New Vaal was established in the early 1980s to service the Lethabo Power Station. In 1985 it delivered its first coal. It is covered by 15 to 22 m of sand and has three coal seams: top, middle and bottom. These seams are mined simultaneously to produce a blend of 15.6 MJ/kg coal for the power station. However, all three of these existing pits have similar SC problems. The top seam does not burn when blasted and whatever coal remains can heat up. Notably, it does not flare into major fires. SC is only serious when previous underground workings exist in the middle and bottom seams. This mine experienced difficulty in preventing SC because of the problem in locating underground workings and locating the bords when drilling (Phillips *et al.* 2011).

### Middleburg Mine

Middelburg Mine is owned by BHP Billiton. It is an opencast mine located near the town of Middelburg in Mpumalanga province. It is the sole provider of coal to the Duvha Power Station

and produces 6 Mtpa coal for the export market. This mine uses draglines to strip the overburden. A combination of shovels and trucks is used to mine the coal at the Boschmanskrans pit. The number two and four seams are mined. SC occurs in the number two seam because of previously mined underground workings. The authors of the Coaltech report *Best practice guidelines for surface coal mines in South Africa* (Phillips *et al.* 2011) observed the following problem areas during a visit to this mine:

- SC occurred around the edges of the pillars; this was visible at several locations in the highwall.
- Spontaneous heating occurred where coal and shale were loaded together.

### Arthur Taylor Colliery (ATCOM)

ATCOM is an Xstrata opencast mine situated in Witbank, Mpumalanga, and produces approximately 4 Mtpa of export coal. In 2003, this mine began surface mining and operates in an area previously mined by bord-and-pillar workings which are referred to as the old Phoenix Village area. The number two and four seams are mined. The number three seam is excluded due to its high sulphur content which could promote SC. This mine has SC problems which stem from previous workings in the northern part of the lease area (Xstrata Coal 2013; Phillips *et al.* 2011).

### Landau Colliery

Landau Colliery is an Anglo Coal opencast mine situated to the west of Witbank, Mpumalanga. Two reserve blocks are mined, namely the Kromdraai and the Excelsior blocks. Kromdraai produces 6 Mtpa, while Excelsior produces 0.72 Mtpa for the export market. Coal is transported about 2.3 km from the pit to the plant. The mine extracts the number one and two seams. Previously, this mine experienced serious SC problems. This was due to the parting between the two seams which required running operations to be conducted in two passes. This led to delays in the removal of the coal, as well as an additional fragmentation to the coal (Phillips *et al.* 2011).

The incidences of SC experienced at the above mines are an indication of the difficulty in trying to manage SC and support the author's contention that SC is a serious problem at coal mines in SA. The effects of SC have to be properly managed. This information will not be used further in this study but has been provided for completeness on the topic.

## 2.12 THE IMPACT OF FUEL PROPERTIES ON SPONTANEOUS COMBUSTION

Very high carbonaceous shales will combust spontaneously under the right conditions, particularly if they contain high levels of kerogen (a mixture of organic chemical compounds) which make up a portion of the organic matter in sedimentary rocks. These shales provide a major source of additional fuel for coal-induced fires.

According to Itay, Hill and Glasser (1989), the most important factor contributing to SC is particle size. Very fine coal does not burn due to a shortage of oxygen. Coarse coal burns and is very reactive. However, the most dangerous combination is a mixture of fine and coarse materials.

The magnitude of the problem depends on a complex relationship of a range of intrinsic and extrinsic factors which will be explained in detail below (Uludag 2001).

### 2.12.1 Intrinsic factors

The main intrinsic factors are as follows:
- Coal composition, rank and petrographic constituents
- Coal variability, particle size and surface area
- Moisture content
- Presence of iron pyrites
- Mineral matter

In terms of the nature of the coal, Guney (1968) classified the important intrinsic factors as being
- pyrites
- moisture
- particle size and surface area

### 2.12.2 Extrinsic factors (atmospheric, geographical and mining)

The main extrinsic factors are as follows:

- Climatic conditions (temperature, relative humidity, barometric pressure and oxygen concentration)
- Stockpile compaction as related to height and method of stockpiling
- Dump consolidation, influenced by height, method of formation and equipment used
- Presence of timber or other organic waste material in the abandoned areas or dumps (Phillips *et al.* 2011)

The pyrite content contains sulphur minerals which may accelerate spontaneous heating. However, it must be noted that pyrite must be present in concentrations greater than 2% before it can have any effect.

The wetting and drying of coal provides an opportunity for heat transfer to occur in coal stockpiles. The drying of coal is an endothermic process (requires heat) which will affect the heat balance in an oxidising pile of coal. The effect of drying will be to decrease the heat available, resulting in self-cooling. The wetting of coal gives off heat and is an exothermic process which accelerates self-heating (Lyman & Volkmer 2001).

During the wetting and drying of coal, heat is transferred between the coal and the air. Conductive heat transfer takes place through the coal and at the surface of the coal pile. The presence of moisture can alter the inherent rate of oxidation. According to Lyman and Volkmer (2001), increases or decreases in heat affect moisture content and oxidation rates and can explain most of the heat generated in the coal. However, there are other factors that contribute to self-heating of the coal, such as the accumulation of loose coal on the floor adjacent to the highwall.

### 2.12.3    International classification of in-seam coals

In 1998 the Economic Commission for Europe (ECE) – United Nations (UN) Working Party on Coal, through the Group of Experts on the Utilization and Preparation of Solid Fuels, developed an International Classification of In-seam Coals. The objective was to create an

instrument that would permit the classification of coals to contribute to the characterisation of coal deposits. These classifications cannot be used for commercial or trade purposes. An accurate assessment of coal deposits requires a clearly defined sampling technique based on existing national standards (e.g. those of Australia or the USA) in conjunction with the classification analysis.

Figures 2.12a and 2.12b illustrate the ECE–UN International Classification of In Seam Coals which is based on rank, petrographic composition and grade. The following points summarise the main international consensus reached on the lower and upper limits of the ranks:

- Lower limit (low rank) – less than 75% moisture content, moisture being bed moisture, that is, total moisture determined according to the ISO 1015 (35) or 5068 (40) standards.
- Upper limit (high rank) – less than 0.8% hydrogen content. Hydrogen content must be determined according to the ISO 609 (33) or 625 (34) standards.

Figures 2.12a and 2.12b delineate the divisions between lignite, sub-bituminous, bituminous and anthracites, or alternatively the low, medium and high rank divisions.

If there is no known reliable parameter to cover the full range of rank, the boundary limits for the main divisions and subdivisions will be based on the specifications as indicated in the footnotes to Figure 2.12a.

A simple washability test could be used to establish the relative amount of finely disseminated mineral matter in the coal. This information is an additional indicator of facies in relation to grade (United Nations 1998).
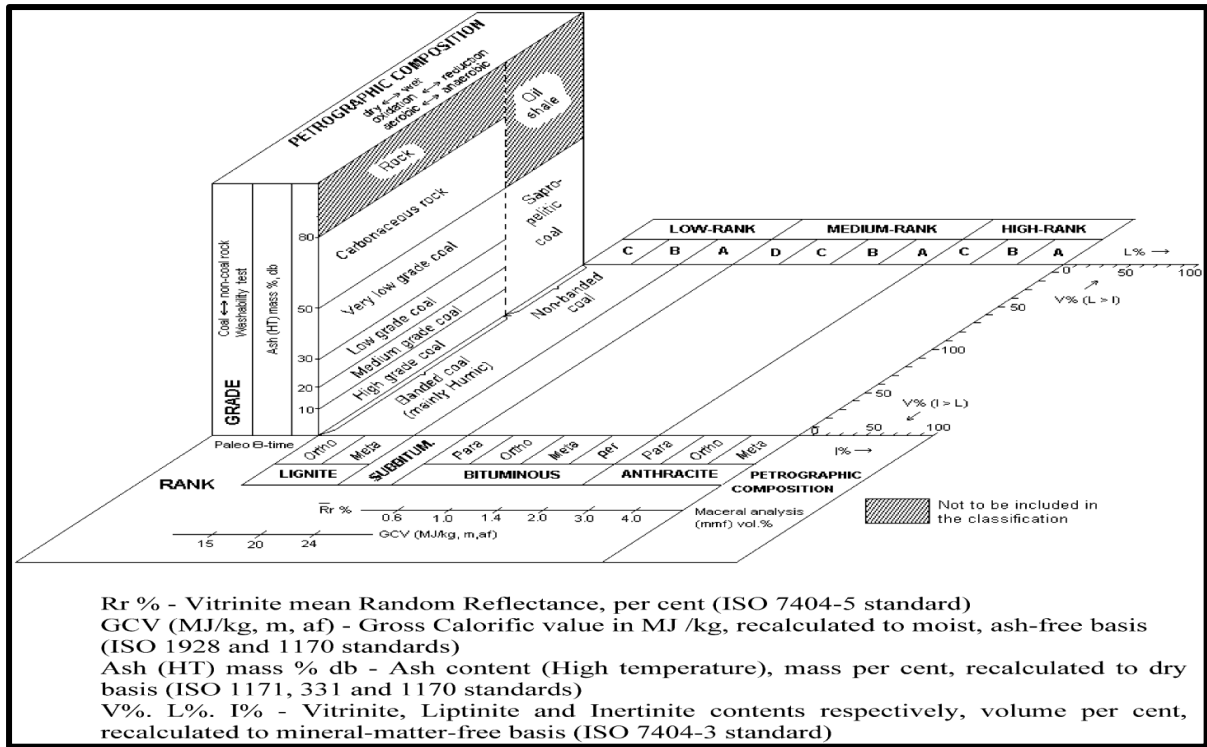
**Figure 2.12a: ECE–UN In-seam Coal Classification view 1 (United Nations 1998)**
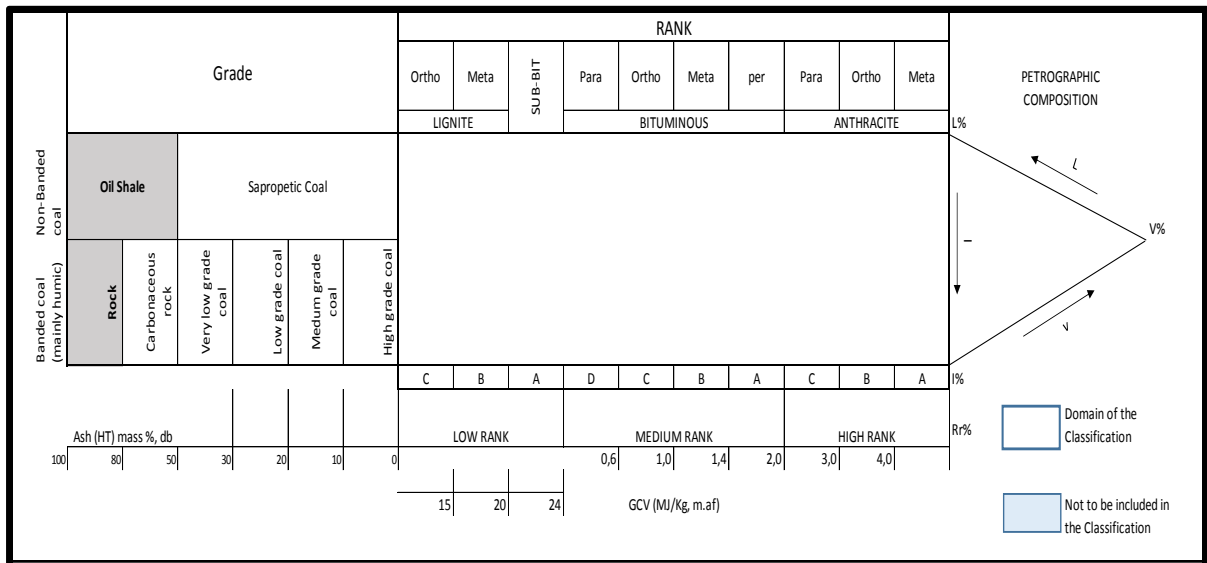


**Figure 2.12b: ECE–UN In Seam Coal Classification view 2 (United Nations 1998)**

A general discussion on fuel properties is very important because the factors set out above will be used to determine the fuel properties of the GG coal. The intrinsic and extrinsic factors give an indication of how SC will affect the different types of coal. The coal at GG needs to be classified according to international standards and this classification will be used in this study.

## 2.13 THE IMPACT OF OXYGEN ON SPONTANEOUS COMBUSTION

According to Adamski (2003), the oxygen absorption rate is a function of the coal's age. Fresh coal is more reactive than old coal or coal that has been exposed to oxygen for longer periods. The reactivity depletes with exposure and oxidation over time.

An energy-transfer model is ruled by natural convection and radiation. Therefore, the energy transfer is dependent mostly on the movement of gases. This movement is also responsible for oxygen transfer into dumps. The following factors contribute to the movement of gases:

- molecular diffusion
- barometric pressure changes
- thermal breathing
- wind pressure
- natural convection

However, there is a problem when rainfall causes erosion at the dumps which exposes more coal to the oxygen in the atmosphere (Phillips *et al.* 2011).

The use of pre-split blasting is avoided since it creates cracks around the highwall which would allow oxygen to enter the old workings.

In underground mines, the primary cause of SC is crushed coal in contact with a sluggish airflow.

### 2.13.1 Oxidation of the coal

Investigations into the SC of coal can be placed into two categories, namely: studies related to the kinetics of the reactions and the associated heat effects, and studies related to the behaviour of dumps, bunkers, silos and ships' holds packed with coal or any other material such as fishmeal, hay, soap or pyrite ore, where the possibility of exothermic reaction exists.

Lyman & Volkmer (2001) explained that the oxidation of coal is a complex process due to the diverse compositions and heterogeneous nature of coal. This can be explained by the following formula (as stated by Adamski 2003):

$$C + O_2 = CO_2 + Heat$$

Oxidation occurs when oxygen reacts with the fuel, i.e. coal. The oxygen in the air is responsible for the oxidation process. The heat generated by this oxidation reaction is minimal. However, under the right circumstances this heat may accumulate and cause the temperature of the coal to rise (Phillips *et al.* 2011).

Depending on the properties of the coal, heating of broken coal left in stockpiles in the cut or elsewhere on the mine can occur after a period of time. As mentioned earlier, the tendency of coal to self-heat depends on the coal type, geological setting, environmental conditions and extrinsic factors (mining related).

The oxidation reactivity of a coal pile is determined by the inherent oxidation reactivity of the coal and its particle size. The inherent oxidation reactivity varies for different coals and depends on the type of coal. For example, low rank coals tend to be more reactive than higher rank coals under the same set of conditions. The rank, combined with the inherent of the coal's particle size, results in an overall oxidation reactivity for the coal which could be regarded as the "pile oxidation reactivity" (Adamski 2003).

This information is important for determining how the entry of oxygen into a coal storage bunker could lead to SC and will be used in this study.

## 2.14    THE IMPACT OF HEAT ON SPONTANEOUS COMBUSTION

In waste dumps containing rejected coal material in unconsolidated heaps where oxygen can come into contact with the coal and heat cannot dissipate, SC starts to occur.

Water vapour can be a trigger for combustion of dumps. Extra heat due to condensation of moisture can lead to unstoppable self-heating if a dump is at a critical temperature and oxygen

is available. Microporosity will also increase the rate of reaction until the particles are smaller than 0.5 mm.

Oxidation processes produce heat. If the heat is dissipated, the temperature of the coal will not increase. However, if the heat is not dissipated, the temperature of the coal will increase. According to Adamski(2003), it has been proved that the higher the temperature, the faster the coal reacts with oxygen. It is interesting to note that GG is located in the Limpopo province, particularly in Lephalale, where the daily maximum temperature can reach up to 45 °C during the summer season. It can therefore be deduced that climatic conditions play a significant role where the initial temperature is concerned.

**Table 2.14: Mean DBT/WBT and associated conditions (Swanepoel 2012)**

| Month | Temperature | | Humidity | Associated conditions |
|---|---|---|---|---|
| | **Mean DB temp** | **Mean WB temp** | **Avg % humidity** | |
| Jan | 26.28 | 20.96 | 57.00 | Period of high humidity months lots of wetness in the atmosphere, high precipitation months, SC very common due to summer rains |
| Feb | 27.19 | 20.00 | 52.00 | |
| Mar | 25.87 | 18.00 | 43.00 | |
| Apr | 21.42 | 15.00 | 47.00 | |
| May | 19.10 | 12.00 | 39.00 | Period of low precipitation months and low humidity months, SC very common due to high winds and dry air |
| Jun | 21.42 | 13.80 | 39.00 | |
| Jul | 15.64 | 9.00 | 40.00 | |
| Aug | 18.39 | 10.00 | 30.00 | |
| Sep | 21.95 | 14.00 | 40.00 | |
| Oct | 23.91 | 17.20 | 50.00 | Period of high humidity months lots of wetness in the atmosphere, high precipitation months, SC very common due to summer rains |
| Nov | 25.25 | 18.10 | 48.00 | |
| Dec | 25.15 | 19.80 | 60.00 | |

According to Adamski (2016), SC is sporadic in the mining area of GG. SC cannot be directly correlated to a season because SC occurs at the mine all year round. As indicated in Table 2.14, the months October to April are regarded as the summer months and due to its location GG tends to have high rainfall during this period. The rainfall is of short duration, with intense

thunderstorms. These months experience high humidity and a wet atmosphere, together with high precipitation. SC is very common during this time as the heavy rains tend to wash away the sealing caps of the dumps, which allows the entry of oxygen, thereby creating SC.

The months of May to September are regarded as the winter months when the temperature is at its lowest. These are low rainfall months with low humidity and are prone to heavy winds. SC is common in these months and the water vapour (steam) is clearly visible on the dumps. Therefore there is no indication that SC occurs more frequently during certain months. There is no factual evidence available to indicate such reasoning at GG mine.

### 2.14.1    Measures to reduce heating

The following measures to reduce heating have been tested:
- Periodic compaction
- The use of a low-angled slope to minimise the effect of wind
- Protection of the coal stockpiles within an artificial barrier and covering them with an ash-water slurry made with fly ash
- The use of wind tunnel tests to design an effective wind barrier

The significance of the information discussed above is to understand the impact of heat containment or release on SC. This information is relevant and will be used in the current study.

### 2.15    THE IMPACT OF MINING PRACTICES

Many factors in both surface and underground mining contribute to the potential SC of coal. For example, damage to sidewalls and the increase in walls as a result of blasting operations in the underground workings, inadequate loading of coal, cleaning techniques, poor housekeeping, blasted material being stored too long before loading, the stockpiling of coal, excavation stability and maintenance are all contributing factors (Phillips *et al.* 2011).

Another excellent example is New Vaal's biggest challenge: it relates to accurate drilling of the blast holes so that holing into the old workings does not occur (Phillips *et al.* 2011).

It is clear that mining practices could influence the occurrence of SC at a mine. This information will be used in the study to formulate how best to improve mining practices.

## 2.16    PREVENTION METHODS

### 2.16.1    Crushing and segregating of material

Itay *et al*. (1989) recommended crushing and segregating material before stacking. They recommended that the fine material be placed on top of the coarse material. The fine material will fill the voids within the coarse material to make a less permeable barrier which reduces or effectively blocks airflow.

Further recommendations were:
- Compact dump surfaces and slopes in order to minimise permeability.
- Stack a thin layer of middlings over the whole dump. This layer, if compacted, could prevent oxygen from entering into the dump because the thin, less permeable layer of middlings would absorb oxygen and restrict the airflow into the dump.

Itay *et al*. (1989) explained that the modelling done on SC of coal has shown that a coal stockpile may be considered to be safe if the material is either so reactive that the reaction is limited to an outer layer where heat can easily be lost at a low temperature, or it is non-reactive and ignition would not occur. Modelling has shown that compacting improves the safety of a stockpile when the material is highly reactive, but could have the opposite effect on low reactive coals (Arisoy, Beamish & Cetegen 2006).

Compaction results in the coal being stored at a higher density due to the reduction of voids, which in turn inhibits the flow of oxygen within the heaps (Adamski 2003).

### 2.16.2    Knowledge of the coal

It is important to "know your coal". Anthracite, for example, has a high carbon content and is less combustible than bituminous coal which has a low carbon content. Freshly extracted coal absorbs oxygen more quickly than coal in mines that have been exposed to oxygen for longer periods. Freshly extracted coal is therefore more likely to heat spontaneously.

In terms of highwalls at surface mines, coal spalling from the seams should not be allowed to remain against the highwall. If the coal is of the type likely to combust spontaneously, loose coal should be cleared promptly. The highwall should be reinforced with soft spoil material if it is to be left for an extended period. The most common technique for treating SC at surface mines is cladding of the highwall.

### 2.16.3    Creating a buffer

Prevention of SC could involve the creation of a buffer which is maintained at a minimum width of 20 m for a 60-m-wide cut. If the bords are not filled with blasted material, air can leak into the underground workings and cause SC. A procedure should be in place to specify that if drill holes have penetrated a bord, it must be plugged immediately as it acts as a chimney (Phillips *et al.* 2011).

### 2.16.4    Use of a mud slurry

As stated before in Section 2.10.1, in China, water mud slurry is injected into the cracks created by subsurface burning or into a series of holes drilled into underground shafts, drifts and slopes. This smothers the flames. The surface is then covered with large amounts of soil to prevent ingress of oxygen into the coal seams.

### 2.16.5    Use of water cannons

High-pressure water cannons have been used successfully to cool heated areas, but in advance headings they have proved ineffective in dealing with large heating areas. The inherent danger in using water cannons is that a water gas explosion can be induced within the old bords, which cannot be ignored. Water cannons are also used to cool the hot coal during loading, which results in water vapour and dust being released into the atmosphere, hampering loading

visibility. In general, water cannons do not appear to have been effective in the prevention or control of SC (Phillips *et al.* 2011).

## 2.16.6    Geometry and maintenance of stockpiles

The height and slope of the stockpiles and dumps are of critical importance. Considerable benefit can be obtained by building dumps in relatively thin compacted layers. Longer-term stockpiles and product coal can be safeguarded by spraying the surfaces with a thin (bituminous) coating to exclude air (Stracher & Taylor 2004).

The time taken for heating to occur varies considerably. Product stockpiles and coal inventory in the cut should not be left longer than the incipient heating period. The Council for Scientific and Industrial Research (CSIR) bunker test can be used to determine the time limits of the product (De Korte 2014b). Both run-of-mine and saleable product coal have been known to be susceptible to SC. A layer of coarse particles at the base and edges of the stockpile may result in increased ventilation passing through the coal. The situation is therefore exacerbated by prevailing hot, moist winds which may lead to a greater risk of SC in summer months, as noted in Section 2.14.

## 2.16.7    Covering with wet fly ash

According to the Coaltech report (Phillips *et al.* 2011), the most effective technique appears to be covering with a wet layer of fly ash from a thermal power station. This could be an option for many large surface mines in South Africa.

This section has briefly discussed the various methods suggested or used to prevent SC at mines. This information will be considered when drafting the guidelines for preventing SC in coal storage bunkers.

## 2.17    PREVENTION METHODS BASED ON MINE DESIGN

A mine's highwall is orientated in a north-to-south direction depending largely on the prevailing wind direction. The position of this highwall means that wind does not force air through the buffer into the open bords if a buffer is present. There is consensus with most mines that buffer blasting of the overburden is the most likely technique to be used to control SC in previously mined areas. The buffer must remain throughout the mining cycle to prevent ingress of air from the highwall. Some mines recommend that the buffer must never be less than a third of the width of the cut (Phillips *et al.* 2011). Blast holes must be sealed immediately after drilling to prevent the ingress of air.

Coal mines should ensure that no more than 100 m of coal is exposed at any time behind the draglines to assist in controlling SC. The maximum time required to mine a cut must be kept to three months to prevent prolonged exposure of coal and overburden, as well as heat within the highwall.

It can be concluded that measures to prevent SC must be considered at the mine design phase of a project. If appropriate knowledge is applied at this stage, costs can be reduced considerably during the normal mine operations. This is relevant to the present study.

## 2.18    PREVENTION THROUGH MANAGEMENT CONTROLS

In Coaltech report (Phillips *et al.* 2011) it was stated that mine personnel had suggested that for effective control of SC both overburden removal and coaling operations should be under one manager.

Some of the reasons for problems experienced at several mines include:
- Newly appointed managers need time to develop an appreciation of the role of buffer blasting in the control of SC.
- The buffer was mined in certain instances.
- There was no clear and documented standard code of practice to deal with SC.

### 2.18.1    Measures for preventing SC

The prevention and reduction of incidents requires:

- Increased awareness of the causes of SC

- Increased use of risk identification management strategies

- Knowledge of prevention strategies

- Early attention to the potential sources of the problem, which may prevent occurrences of heating progressing to full-scale SC

- Use of methods for dealing with SC in different circumstances

- Capping of tailings (plant rejects) dumps with at least 1m of inert material, adding topsoil and revegetating the whole area

- Placing of coarse reject (discard) material in layers and compacting it using a roller, on the edges of the dump, to minimise the infiltration of oxygen

There must be a good understanding of the SC problem at the mine and an established system for preventing and controlling SC.

The mine must have an SC document which outlines key performance indicators (KPIs) for the prevention of SC, among them:

- Single-cut operations

- Drilling crew being responsible for plugging all the vent holes

- Formation of an SC team to plan and measure the performance of each section

- Raised awareness of SC throughout the mine

- Solving the problem progressively, with an improvement from cut to cut

An assessment of the self-ignition hazard must be done for each mine site. The important parameters in the heat balance and self-heating are:

- Coal particle size

- Quantity mined

- Calorific value of the coal

- Opportunities for heat conduction

- Geometry and dimensions of the mining operation or coal storage facility

- Heat transfer coefficient on the outside surface of the bulk blasted stockpile or dump

- Ventilation

- Degree of compaction

## 2.18.2 Measures for controlling SC

The control of SC can be achieved by using a combination of techniques. The control measures that can be applied in South African collieries are listed in the following groups:

- Control measures to reduce and eliminate oxygen from the process
- Use of scaling agents
- Dozing over
- Buffer blasting
- Cladding of the highwall
- Measures to reduce the temperature of the coal in dumps, stockpiles or bunkers and hence the reaction rate
- Water cannons used on the highwall, in front of the dragline and during coaling
- Nitrogen injection into old workings
- Carbon dioxide injection into old workings
- Removal of fuel sources
- Excavation of hot or burning material

Whether or not these control measures are effective will depend on individual situations such as mining layouts and the extent of the SC problem.

As shown above, various prevention and management controls can be applied to SC, some of which are directly relevant to solving the problem of SC at coal storage bunkers. The other information is provided for the sake of completeness.

## 2.19 PREVIOUS WORK DONE ON SPONTANEOUS COMBUSTION IN CONFINED SPACES – SHIPS' HOLDS AND BUNKERS

The major modes of coal transportation are railroads, unit trains, barges, ships and trucks. In SA, coal is transported by road/rail to inland users and the RBCT (Ekmann & Le 2004). The following basic rules will assist in the prevention of SC:

- Do not load hot coal onto trucks.
- Trim coal to an even level.
- Do not mix wet and dry coal (De Korte 2014a).

Coal has relatively low energy content per unit weight and competes on the market with other fuels as a lower cost fuel for power generation. In Israel, extensive simulation experiments pertaining to the oxidation resistance of various stored coals was conducted and documented by Ekmann and Le (2004).

Stored coal comes into contact with atmospheric oxygen and undergoes a decrease in temperature (releases heat) which can result in autocatalytic self-heating of the pile. However, this can only be sustained if the heat produced by the exothermic oxidation-related reaction cannot be dissipated by heat transfer within the stockpile. If the stockpile temperature increases above 30 °C, then vaporisation of the moisture content of the coal takes place, as well as the emissions of lower molecular weight hydrocarbons and carbon monoxide. The vaporisation and emission rates of gases increase with temperature. These products decrease the ignition point of the coal. Coal stored in confined spaces such as ships' holds, silos, bunkers and rail wagons is most susceptible to self-ignition if the duration of the storage is more than a month. The autogenous heating of stockpile coal is restricted to small distinct areas, referred to as hotspots, which are characterised by good oxygen diffusion and insufficient heat transfer. The oxidation-induced autogenous heating of coal causes a loss in calorific value of the reacted coal and also causes safety and handling problems. In the lower temperature range, only a small portion (<25%) of the oxygen consumed is emitted as gases (Grossman, Davidi & Cohen 1995).

Grossman *et al.* (1995) observed bituminous coal of a wide geographical and geological variety and found that the oxidation of small quantities (1–20 g) of coal samples at a relatively low temperature (45–150 °C) in batch glass reactors was accompanied by the release of molecular hydrogen in small amounts. They looked at samples of Colombian, Australian, American and

South African coal and categorised them in terms of particle size, oxidation rate and amounts of hydrogen produced.

The international maritime trade in bituminous coal is growing rapidly due to low and stable prices. However, bituminous coal stockpiles stored in the open air can undergo autocatalytic heating, which is accompanied by the emission of small amounts of molecular hydrogen. If coal is contained in a confined space, for example, a ship's hold and the temperature rises to 40 °C, an accumulation of hydrogen is expected. The explosive risk of hydrogen must be considered.

Grossman *et al.* (1995) examined the possibility of the accumulation of hydrogen locally above the lower explosive limit (LEL) of coal, which might initiate a chain reaction leading to an explosion. The authors examined such a situation occurring inside a ship's hold loaded with bituminous coal.

The mine can employ the following solutions to assist with the management of SC at the bunker:
- Do not mix wet and dry coals.
- Prevent oxygen from entering the bunker.
- Monitor the duration of storage in the bunker.
- Ensure there are no areas in the bunker where hot spots can form.
- Bear in mind that particle size could have an impact on SC.
- Bear in mind that the oxidation rate and the amount of hydrogen produced could cause explosions in the bunker.

## 2.19.1    Fires in ships' holds

The international maritime trade in bituminous coal amounts to about 350 million ton per annum, with different types of vessels/ships used as the mode of transportation. Coal shipped out of SA is transported in large Capesize vessels (120 000–180 000tons).The problem of self-heating due to coal oxidation is considered to be the main cause of deterioration in calorific value in the ship's hold and severe ship fires.

To examine the possibility that the hydrogen concentration in the space above the coal pile in a ship's hold could reach the LEL, Grossman *et al.* (1995) used a typical Capesize coal vessel (150 000 tons) as an example. The dead space of air above the trimmed body of coal may be up to 1m deep directly beneath the hatch. In this pocket the molecular hydrogen produced by the heated oxidised coal is expected to accumulate. A rough estimate of the dead space is 500 m$^3$. Some of the hydrogen may be absorbed inside the pores of the coal.

Data captured at loading ports indicate that coal is loaded at atmospheric temperature (20 to 30 °C). An increase of 2–10 °C occurs during a voyage of three to four weeks. In certain cases, cargo bound for Israel reaches 50 °C. However, as loading temperatures are dictated/governed by the International Maritime Organisation's(IMO) procedures, as well as by national regulations in countries such as SA and Australia, the coal cannot be loaded aboard a vessel if the temperature is above a certain level (45 °C). According to the IMO, if a cargo temperature exceeds 55 °C, the vessel should sail to the nearest port that can offer suitable assistance.

There have been cases where coal cargoes self-heat and reached severe self-ignition. The temperature selected for the calculation of the concentration of accumulated hydrogen in the hold is 40 °C. The emission rate of hydrogen can be calculated by taking the reported activation energy for the production of hydrogen, namely 47.7 kJ mol$^{-1}$. In order to assess the possible accumulation of hydrogen in the ship's hold during extended voyages, the following parameters have to be estimated: length of the voyage, amount of coal in the hold, volume of reacting oxygen, rate of oxygen consumption by the coal, volume of free space where hydrogen will accumulate, average temperature of the transported coal and type of coal shipped.

However, some of these parameters are dependent on the import and export countries. Israel imports coals from SA, Australia, Columbia and the United States. All the coal examined emitted significant quantities of molecular hydrogen, despite the variation in rank, ash content and provenance.

The risk evaluations done by Grossman *et al.* (1995) were based on the assumption that the ship's hold behaves similarly to a closed batch reactor. If the hold has some gas exchange with the outside temperature, the following processes will occur:

- Increased rate of hydrogen production due to the continuous supply of oxygen
- Dilution of the hydrogen, preventing the build-up of dangerous concentrations

The IMO dictates that a ship's hold should be aerated under circumstances where explosive gases can accumulate. The confined space must be ventilated. The results of this test study revealed that the ingress of oxygen must be prevented because hydrogen and other explosive gases are directly correlated with the consumption of oxygen. Alarms and gas detectors are not geared to measure hydrogen emissions. Therefore the risk posed by hydrogen emissions is mostly overlooked in current practice (Grossman *et al.* 1995).

It must be noted that the IMO Protocols and Guidelines have changed since the 1990s. All ships are now legally obliged to carry gas-monitoring equipment in order to control and detect problems before they arise (Falcon 2014).

Explosions in confined storage facilities are reported frequently, which results in the loss of lives mainly in deep mines and large silos. These explosions can be attributed to the accumulation of increased concentrations of methane and occurrences of large amounts of increased surface dust which are normally associated with the atmosphere of the mine. It is suggested that in order to prevent these occurrences, efficient ventilation and filtration of the dust and online monitors be installed in mines. In ships' holds, there are no measures taken to detect the presence of dust. However, explosions still occur in instances where there is no indication of methane or dust accumulation. (In 1994, in SA, a mine was shut down owing to fires and possible explosions which resulted in the loss of 18 lives.)

### 2.19.2  Fires in coal bunkers

SC is a recognised problem in stored coal. Research has shown that there are three overlapping processes which take place below 120 $^{\circ}$C. These processes are:
1. *Intrinsic oxidation*, which starts at temperatures of approximately 15 $^{\circ}$C and occurs mostly with low rank, high oxidation coal. Iron pyrites and iron sulphides in the coal combine with water and $O_2$ to form iron sulphate and sulphuric acid (Yang, Wu & Li 2011). These reactions are exothermic and can provide the triggering temperature to start the hydrocarbon and carbon reactions with entrained oxygen in the coal. SC will not occur if the heat generated from this intrinsic oxidation and/or pyrites reaction is removed as it is

generated. However, heat retention at its source of generation could lead to the second stage of oxidation.

2. *Surface oxidation*, which starts at 30 $^{o}$C, is conditioned by active centres on the macro-surface of the coal and which increases with the rise in temperature and becomes self-accelerating. This process is inhibited if water or wetting agents are applied in a manner that blocks the coal surface from contact with air. If sufficient $O_2$ is available and the dissipation of heat is poor or non-existent, then oxidation will proceed to the third stage.

3. *General oxidation*, which starts at temperatures of approximately 70 $^{o}$C. Temperatures above this creates a change in the coal substance. The effect of this change appears to be an increase in the available surface area and consequently a marked acceleration in the rate of oxidation. Sufficient $O_2$ in the process can push the reaction temperature up to about 250 $^{o}$C at which point the oxidation becomes spontaneous. Ignition is achieved at 350 $^{o}$C.

These three stages overlap in practice. In general practice, where coal is piled in a storage yard and extended periods of idle storage are required, recommended techniques for the geometry, packing, sizing, surface protection and periodic monitoring by temperature probes have been developed. It is recognised that coal is going to remain static long enough to produce SC if the oxidation process is allowed to start. However, the timing for this process (how long) would depend on the coal. Lower ranking coals have a high oxygen content and therefore a higher propensity for SC. Fires can occur after one to two weeks or two to three months of idle storage (Vollmer 1977).

Once coal is transported into the feed bunkers of a power plant, it is no longer in idle storage but in a continuous flow pattern through the bunker, the coal feeders and the pulverisers, and then burned. If this continuous flow pattern is maintained for all of the coal put into the bunker, if the coal is not already at or near the SC point when delivered to the bunker and no low temperature combustibles (paper, wood, or rags) have been introduced into the bunker along with the coal, then no fires will develop in the coal bunkers. Ideally, a power plant bunker would have from 24 to 36 hours' storage when full, so the retention time of the coal in the bunker should be much less than the oxidation process time to combust spontaneously.

However, this ideal is not always realised and coal fires in bunkers are a frequent problem. If the boiler drawing coal is shut down, the coal flow will cease. The danger in the majority of

coal bunker fires is coal hang-up in various areas of the bunker. This is a result of obstructions in the coal flow path, coal segregation, moisture and inadequate design of the bunker itself. Coal trapped in areas of the bunker over a period can induce conditions for SC (Vollmer 1977).

An example of how to mitigate fires in a coal bunker was demonstrated at Cleveland Electric Illuminating Company in Ashtabula, Ohio (USA) whereby they replaced internal bunker bracing beams with 10-inch pipe sections. The round pipes caused less obstruction to coal flow than the beams. This plant also reported that it is beneficial to periodically run the bunkers at a low level, utilising workers in safety harnesses equipped with breathing gear in the bunkers to clear idle coal pockets and ensure a clean bunker (Vollmer 1977).

In summary, SC prevention techniques in a coal bunker are:

1. Optimum design of the coal bunker to minimise stagnant coal areas. When this situation was compared to the current coal bunker as shown in Figure 1.2c, the design shows specific areas where coal can stagnate and cause hot spots.

2. Sufficient downspout length between the bunker outlet and the feeder inlet to maintain an effective air seal when pulverisers are used

3. Use of heavy-duty mechanical rappers when the feed to the bunker has been cut off and the bunker has been emptied

4. The use of coal with less susceptibility to oxidation; this is seldom an option to plant operators

5. Minimising oxygen availability to the bunker; this can be done in two ways: through the blocking of air infiltration, and/or inert gas blanketing

6. Fitting units with flue gas clean-up systems; the cooled clean flue gas could be utilised as a seal gas

7. Continuous insertion of $CO_2$ into the lower bunker outlets, which is also beneficial in reducing fire potential, although the operational cost of such a system is highly limiting

8. Ensuring that external sources of heat, such as steam lines, are not in close proximity to the bunker walls (Vollmer 1977)

### 2.19.3 Detection

Since it is simply not possible to eliminate fires in some bunkers, early detection is essential. The following points can be considered for the early detection of fires in bunkers:

1. The placement of thermocouples around the bunker could provide continuous monitoring.
2. For the protection of coal feeders, it is prudent to have thermocouples installed on the downspouts from the bunkers.
3. The installation of a sensitive gas-sampling system could provide the first warning that a bunker fire has started (Vollmer 1977).

The case of coal storage in a ship's hold has been used as an example to highlight the seriousness of SC in confined spaces. The recommendations can be extrapolated to the current topic of SC in bunkers at GG Coal Mine and the information may be used to improve the solution to the problem being addressed.

## 2.20   INNOVATIVE SOLUTIONS

Coal fires are very difficult to extinguish. Technologies to prevent mine fires have been developed and applied internationally. These include water and grouting injection, gelatum infusion, inert gas injection and so forth. However, traditional technologies have limitations in preventing fires in high caving. High molecular gelatum and foamed resin are expensive. Inert gases are prone to diffusion with airflow. Water and grouting injection easily flow away along the cracks of the tunnel roof. However, these methods cannot efficiently prevent SC in the tunnel fall of ground.

The three-phase foam technique, developed in China, can be applied in the prevention of spontaneous coal combustion. It presents the advantages of both grouting and inert gas foam in controlling fires(Wan-Xing *et al.* 2011).

Approximately 75% of fires occur in the coal mines in India. It is therefore not surprising that a mechanised device for spraying afire-protective coating material to prevent SC in the coal benches of opencast mines was developed in India. In opencast mines, the main factors responsible for bench fires due to SC are:
* The presence of micro- and macrocracks in the bench walls which allow the entry of air
* Long exposure of the bench walls to the open atmosphere

- Accumulation of loose coal on the bench floor (US Department of Energy 1994)

During coal blasting, some portions of the bench walls develop cracks that may be micro or macro. These cracks allow the entry of air which leads to coal oxidation and heat build-up. It is essential to apply suitable fire-protective coating material over the coal surface to cut off the contact of air with the coal surface and thus prevent SC.

The mechanised spraying device used in India consists of a storage vessel for storing fire-protective coating material and another storage vessel for the storage of raw water, connected to a diesel-operated engine driving the equipment through which the fire-protective coating is delivered through a flexible hose to the spray nozzle. The device is capable of spraying the fire-protective coating up to a height of 20 m over the exposed coal surface (Singh & Singh 2004).

This section illustrates that new and innovative methods are being applied to solve the problem of SC around the world. However, this information will not be used further in my study.

## 2.21   CASE STUDY: GG MINE –SPONTANEOUS COMBUSTION PROBLEM

GG is the largest opencast coal mine in SA and is located within the Waterberg coalfields in the south-western part of Limpopo province. The coalfield is relatively small in area but contains approximately 50% of the coal reserves in SA.

The coal deposit forms part of the Ecca Group and the second coal-bearing zone can be distinguished. The coal seam mined at GG forms part of the upper and middle Ecca. The upper Ecca is an average of 60 m thick and consists of successions of interbedded shale and bright coal. It is a multi-seamed deposit consisting of coal beds varying in thickness from a few centimetres to just more than 1m, closely interbedded with mud stone over the total thickness of 60 m. The middle Ecca forms the lower part of the deposit and is on average 50 m thick, consisting of dull coal and carbonaceous shale, as well as grit and sandstone (Faure *et al*. 1996).

Since the early 1980s, SC problems at GG have been investigated by many researchers, one of whom is Prof. D Glasser, from the University of Witwatersrand, who made important contributions to the subject, as well as recommendations for preventing SC. According to

Glasser (Itay *et al*. 1999), the major reaction of coal is the absorption of oxygen and the release of heat, which reaction is dependent on many contributing factors. Adamski (2003), by way of his research, also made important contributions to the problem at GG. He constructed a geological model according to the geological contacts that apply to the various mine benches.

GG has the largest coal-washing facility in the world. Clean coal production amounts to± 16 mt per year and consists of three products, namely coking coal, power station coal and metallurgical coal. As the raw coal has a high ash content, large coal beneficiation plants are required to meet the production targets.

The raw coal feed from the Volksrust Formation consists of intercalated shale and bright coal layers. Therefore the first step in the beneficiation process is crushing of the raw coal into finer sizes. The intermediary coal product is then separated from the waste material. Thereafter the product is split into a middlings product (power station coal) and coking coal during the secondary washing stage. The following separation processes are used in the different plants: static drum heavy medium, cyclone heavy medium, spiral classification and hydrosizer classification.

During the beneficiation process the mine produces 17 000 000 tons per annum of plant discards. These have a relatively higher propensity for SC due to their higher carbon content. The interburden material is also prone to combustion due to its carbonaceous nature. The large quantity of waste requires safe storage and a disposal method that will prevent the occurrence of fires (Adamski 2003). Table 2.21 lists the waste material from GG.

**Table 2.21: Waste material produced by GG Mine (Adamski 2003)**

| Material | Production (Mt/year) | Volume (Mm³/year) | RD | Ash (%) | CV (MJ/hg) |
|---|---|---|---|---|---|
| Overburden | 12.29 | 6.83 | 1.8 | | |
| Discards | 17.32 | 9.12 | 1.9 | 71.88 | 5.88 |
| Interburden (B7A & B8) | 5.28 | 2.93 | 1.8 | 77.76 | 2.53 |
| Interburden (B10) | 1.72 | 0.91 | 1.9 | | |
| Total | 36.61 | 19.79 | 1.85 (av.) | | |

The discard materials are mixtures of discards from various plants and waste from benches with unknown properties. According to Adamski (2003), a lack of detailed knowledge and the

material properties, as well as the following factors complicate the design of a safe heap: general problems with sand cladding of the highwall leading to heating; visibility problems during loading due to particulate matter generated by hot coal; turnover of management leading to loss of continuity in terms of combating SC; and the spoil side of the operation constituting a major problem, with the spoils material burning.

A mine air-monitoring system is used to monitor the panel returns continuously for $O_2$, $CO_2$, CO and $CH_4$ as required by the Department of Minerals and Energy [DMR] 2002.

This section indicates what work has previously been done on SC at GG(where the problem of SC in coal storage bunkers exists) and is very relevant to this study.

## 2.22    CONCLUSION

Many theories about the relationship between SC and the inherent characteristics of coal have been reviewed and discussed above. However, there are limited publications on best practice for dealing with self-heating of coal under operational conditions. It has been clearly established that SC of coal is a fire initiated by the oxidation of coal. According to Adamski (2003), the dissipation of heat versus the generation of heat is one of the principles on which SC theory is based. This means that the temperature in a coal pile or bunker depends on the rate of oxidation, expressed in units such as millimetres of oxygen per kilogram of coal per day. This is true for oxidation but, as explained above, this is not the only factor contributing to SC.

SC in stockpiles and dumps can be controlled by handling the high-risk materials in a way that limits their contact with oxygen. The only effective preventative technique must be based on preventing air from coming into contact with any coal that is prone to SC. This is because the source of fuel is the coal being mined and the potential source of heat is the oxidation of that fuel.

This chapter has identified factors such as the classification of coal, bunker design considerations, management and control techniques that will be used to create guidelines for design engineers to prevent SC in storage bunkers.

The aims of this chapter have been the following:

- To gain a detailed understanding of SC and how it affects the SA coal mining industry
- To gain an understanding of the self-ignition of coal and the factors affecting SC
- To gain an understanding of how SC affects mines globally
- To highlight the risks associated with SC
- To gain an understanding of what methods exist to prevent, detect, monitor and manage SC
- To gain an understanding of the different tests done to understand and predict SC
- To investigate how SC is being managed at mines where it is prevalent
- To understand how coal is classified and to determine the fuel properties of the coal in GG Mine
- To understand the impact of oxygen ingress into coal storage bunkers
- To understand the impact of heat containment or release in coal storage bunkers
- To investigate some methods currently being used at mines to prevent SC and the management controls being applied
- To review previous work done on SC in bunkers and silos, and to investigate how this work can be used to solve the current problem
- To look at what new, innovative methods have been tried and tested to prevent SC at mines around the world
- To indicate what work was previously done at GG Mine to solve the problem of SC

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# CHAPTER 3
# RESULTS

## 3.1    INTRODUCTION

It has been established in the literature review that SC is a very complex issue. Despite all the research done on SC, there is no single solution that solves all the problems associated with it. This was confirmed by the interviews that were conducted with specific individuals from the industry. The interviewees came from different backgrounds and companies. Most of them concurred that every situation has to be evaluated on its own merit and, if possible, a solution should be found to resolve that particular issue.

The results given in this chapter deal with the major relevant questions pertaining to SC. These results were arrived at from the knowledge gained through the literature review, from the field research done and from the interview feedback, as illustrated in Figure 3.1. Each of these aspects is dealt with in this chapter.
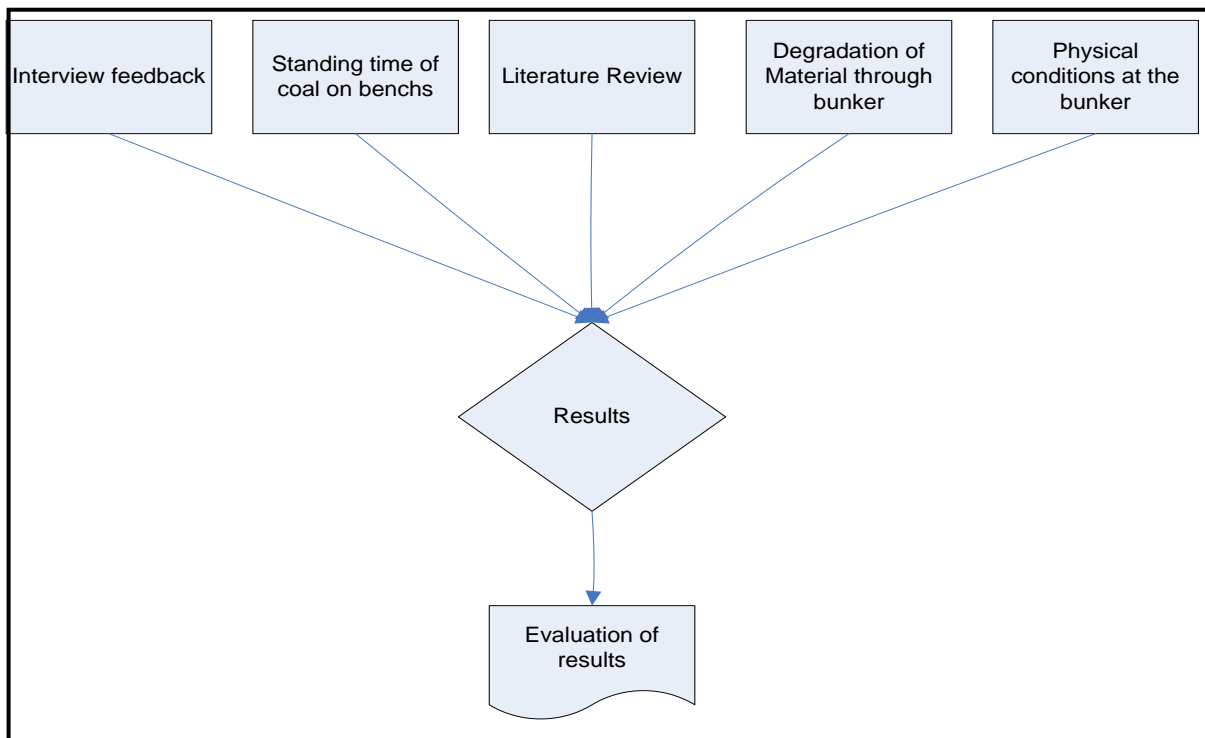


**Figure 3.1: Structure of information flow**

## 3.2    INTERVIEWS

The interviews took the form of informal strategic conversations. The literature review was used to design the questions and topics for discussion.

At the start of each interview, the context was explained to the interviewee and permission was requested to record key statements during the interview by way of handwritten notes in order to clarify and validate the notes with the interviewee.

The data obtained from the interviews were not analysed via any quantitative method. The purpose of the interviews was to gain insight into how SC could be prevented, and how it could be managed in bunkers and silos. The analysis was guided by themes developed during both the literature review and the actual interviews. An attempt was made to find specific issues under these themes for consideration when designing bunkers and silos and for preventing and managing SC in them. The aim was to use the results to create a decision analyser which can be used in a meaningful way.

## 3.3    FIELD RESEARCH

It was critical to start the field research by mapping out the process from the ore body to the storage bunker to ensure that the limits of the study were identified. Data were collected relating to different parts of the process. The collated information from the field research was then analysed using inputs from previous sources in order to find possible solutions to preventing SC in bunkers (Figure 3.1). The focus was therefore on the type of coal being supplied to the bunker, the mining practice and the physical conditions around the bunker, such as wind direction, temperature, and airflow in and out of the bunker.

## 3.4    TYPE OF COAL SUPPLIED TO THE BUNKER

Coal analysis is based on the international classification of in-seam coals and in terms of this classification, four characteristics of coal will be examined, namely the rank of the coal, the grade, the sulphur range and the petrographic composition.

### 3.4.1 The rank, grade, sulphur range and petrographic composition of coals

The *rank* of a coal refers to the degree of maturity of the coal. It is dependent on the degree of metamorphism, i.e. the properties of vitrinite, which is largely responsible for the coking properties of a coal. Therefore the greater the vitrinite content, the greater the coking properties or carbon content of a coal. Vitrinite reflectance is a direct measure of the rank of a coal, which is provided through petrographic analysis.

The *grade* pertains to the amount of impurities in a coal. This is the quantity of inorganic material or ash left after complete combustion. Table 3.4a shows the benches of coal seams with the rank, grade and sulphur range.

To establish the rank, grade and sulphur range, a statistical analysis was conducted using a database of 5 000 exploration boreholes. The data were separated into the different benches with their respective ash contents and calorific values. The information was cross-checked with the ECE-UN International Classification of In-seam Coal as per Figures 2.12a and 2.12b. The information was then set out according to the different benches.

The same exploration borehole dataset was used to establish the sulphur values for the different benches. The sulphur values varied significantly on the different benches. The data were separated into average, maximum and minimum values, and are presented in Table 3.4a. The relevance of this information is to gain an understanding of the chemical properties of the coal being used in the process.

**Table 3.4a: Grade, rank and sulphur range of coal seams**

| Bench | Grade | Rank | Sulphur range average |
|---|---|---|---|
| 2 | Very low grade coal | Ortho lignite- Low rank C | 1.41 |
| 3 | Carbonaceous rock | Ortho lignite- Low rank C | 1.26 |
| 4 | Carbonaceous rock | Ortho lignite- Low rank C | 1.14 |
| 5 | Carbonaceous rock | Ortho lignite- Low rank C | 0.86 |
| 6 | Very low grade coal | Sub Bituminous- Low rank A | 2.00 |
| 7B | Very low grade coal | Sub Bituminous- Low rank B | 1.79 |
| 9A | Very low grade coal | Sub Bituminous- Low rank A | 2.53 |

### 3.4.2    Petrographic composition of coal at Grootegeluk

To understand the variations in the physical and chemical properties of the coal at GG, a petrographic analysis was important. Petrographic analysis is performed to characterise coals, to confirm expectations of the coals and to assess their utilisation potential (ALS Coal Technology 2015). The petrographic analysis will provide valuable information that can be used to establish how the coal will react under different sets of conditions.

A composite sample from each plant was sent to an external laboratory for evaluation. The objective was to determine the properties and evaluate the quality of the composite sample. The analytical method used was one in which a polished block of the sample is prepared and analysed in accordance with the standard methods for petrographic analysis of coal samples. The maceral composition and reflectance rank are quantitatively determined and a qualitative microscopic investigation is conducted to detect signs of detrimental factors such as contamination or oxidation. This information was returned to the Mine for further analysis and record-keeping. The dataset provided information on the maceral composition, such as vitrinite, exinite, inertinite, reactive semifusinite and mineral matter. The data provided were in the form of current mean values as per the prediction model and the new mean values as per the sample. This information was then analysed and used to establish how reactive the coal is for the different benches.

The petrographic report provided more information than just maceral composition. Other useful information, such as chemical properties, rheological properties and coal ash content were obtained from this analysis. However, for the purposes of this study only the maceral composition is used.

Table 3.4b shows the petrographic composition of the different GG benches. Figures3.4a and 3.4b show that the greater the percentage of vitrinite and exinite in the composition, the greater the reactivity. Also, the greater the percentage of inertinite, the lower the reactivity of the coal.

**Table 3.4b: Petrographic composition of benches (Roux 2014)**

| Bench | Reactivity | Vitrinite & exinite | Inertinite | Reactive semifusinite (RSF) |
|-------|-----------|---------------------|------------|------------------------------|
| B2 | 77.44 | 74.52 | 5.51 | 2.96 |
| B3 | 73.59 | 68.67 | 7.51 | 4.91 |
| B4 | 72.41 | 66.57 | 8.67 | 5.84 |
| B5 | 71.01 | 65.02 | 9.25 | 5.99 |
| B6 | 20.71 | 21.42 | 42.36 | 9.46 |
| B7B | 2.20 | 7.18 | 42.25 | 6.96 |
| B9A | 0.00 | 5.01 | 60.16 | 7.44 |
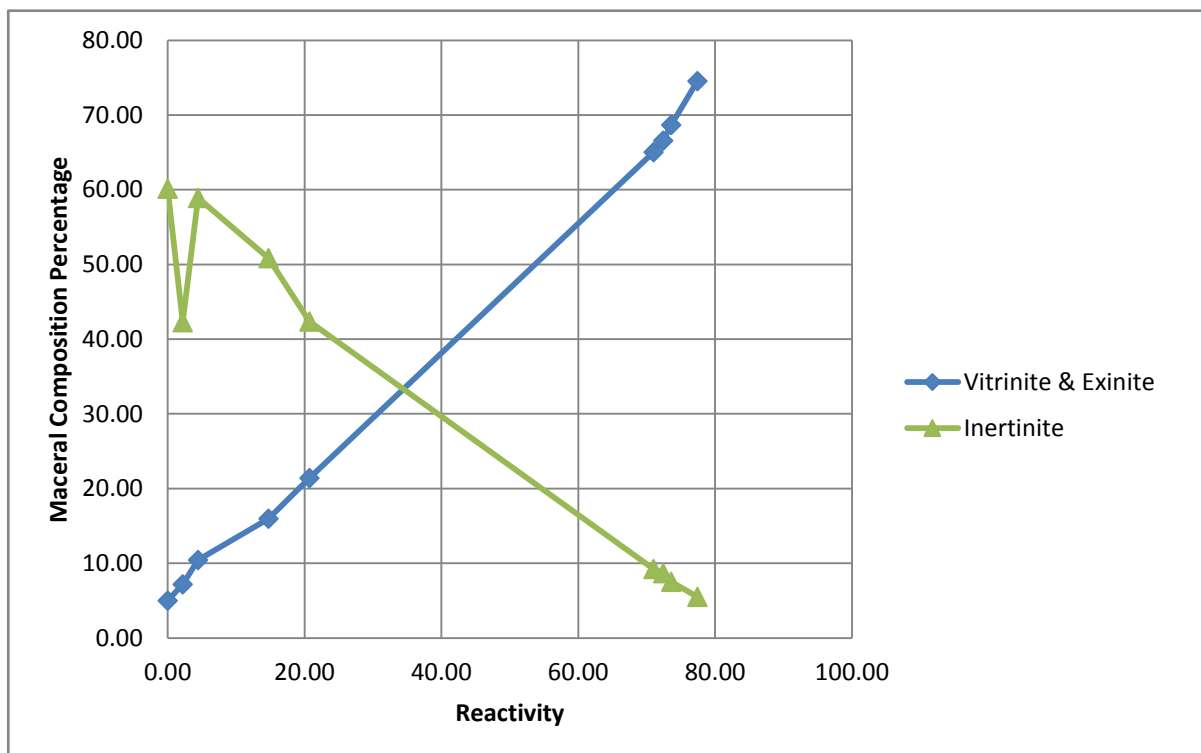


**Figure 3.4a: Reactivity vs maceral composition (Roux 2014)**

The maceral analyses of these coal seams indicate that vitrinite is the dominant maceral. Inertinite, liptinite and reactive semifusinite (RSF) occur in minor proportions. The vitrinite content increases upward in the formation with a concomitant decrease in inertinite and RSF.

The upward increase in the vitrinite concentration is associated with an increase in the energy of the dispositional environment, which is considered to have been instrumental in the enhanced preservation of the vitrinite. The vitrinite reflectance ($R_{max}$) of the GG formation (mean 0.74%) and palynological evidence indicate that the GG formation has been subjected to maximum post depositional temperatures of about 100 $^{o}$C (Faure *et al*. 1996).
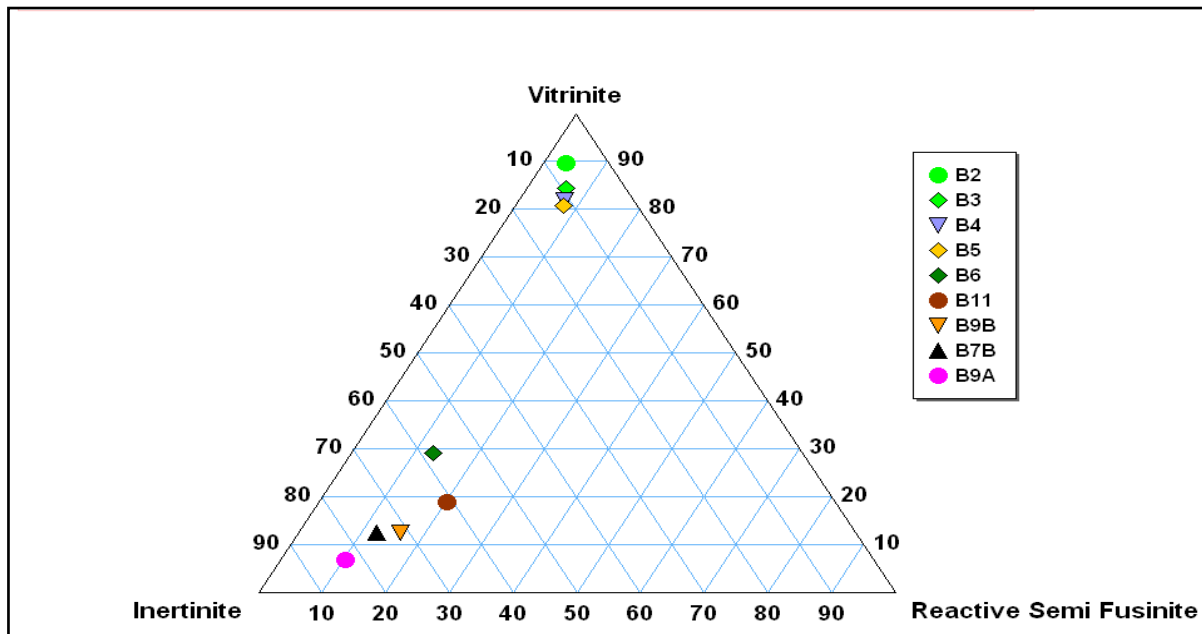


**Figure 3.4b: Petrographic maceral composition (Roux 2014)**

## 3.5    MINING PRACTICE

### 3.5.1    Standing time of loose cubic metres (LCM) on the benches

The mine's short-term planner provided information on the blasting, loading and hauling schedules for the different benches. This information was then analysed and presented as the average standing times for the LCM on the different benches.

It was determined from the mine's short-term production schedule, as per Table 3.5, that material fed to plant GG8 had a standing time of ± 2 weeks on average and that material sent to plant GG7 had a standing time of ± 6 days on average. However, this varies from time to time depending on the production situation. There is no standard available for the standing time

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of material on the benches. This information is necessary to ascertain whether the coal starts to combust spontaneously on the benches before it is fed to the bunker.

**Table 3.5: Standing time of material on the benches**

| Bench | Average standing time (LCM) in days |
|-------|-------------------------------------|
| B2 | ± 2 weeks |
| B3 | ± 2 weeks |
| B4 | ± 2 weeks |
| B5 | ± 2 weeks |
| B6 | ±  6 days |
| B7B | ± 2 weeks |
| B9A | ± 6 days |

### 3.5.2     Particle size distribution (PSD)

Samples of the coal were taken before it was fed into the ROM bunker and at the exit from the bunker to establish the size difference of the particles as they flow through the bunker, as per Figures 3.5a and 3.5b. Figure 3.5a indicates the sampling points and Figure 3.5b shows the results of the two tests. The bunker is 22 m in height. It was critical to ensure that the bunker was empty and at its lowest level when the samples were taken to obtain the degradation results.

A screen analysis method was used to do the sampling. The analysis was conducted using different aperture sizes (in millimetres) to evaluate the samples. The fraction mass was reported as a percentage of the different aperture sizes. The aperture sizes ranged from 0 to 150 mm.

Figure 3.5b shows that 14.8% of the material fed into the bunker is –4 mm. However, when the same sample was taken at the discharge end of the bunker, the –4 mm material increased from 14.8 to 20%. The reason for this test was to ascertain whether the ratio of coarse to fine materials can affect the flow of air in the bunker.
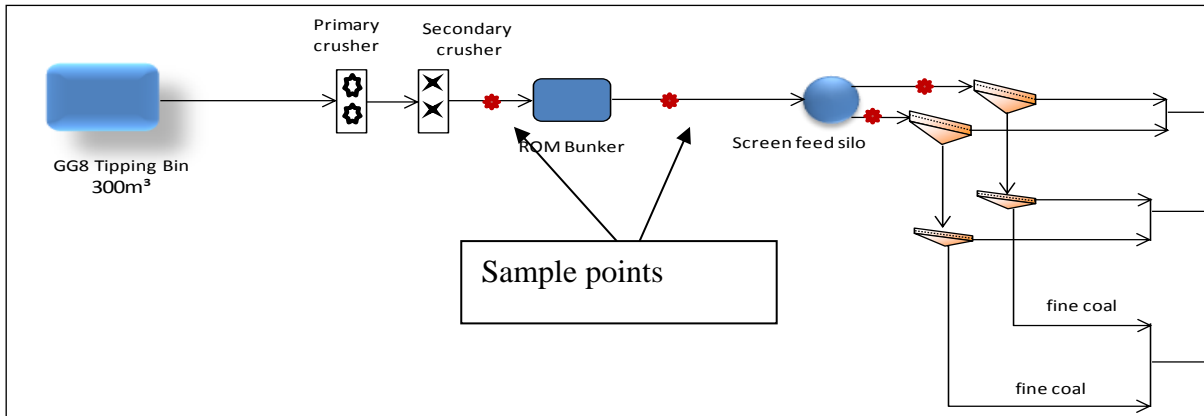
**Figure 3.5a: Sample points for PSD test (Sekano 2014)**
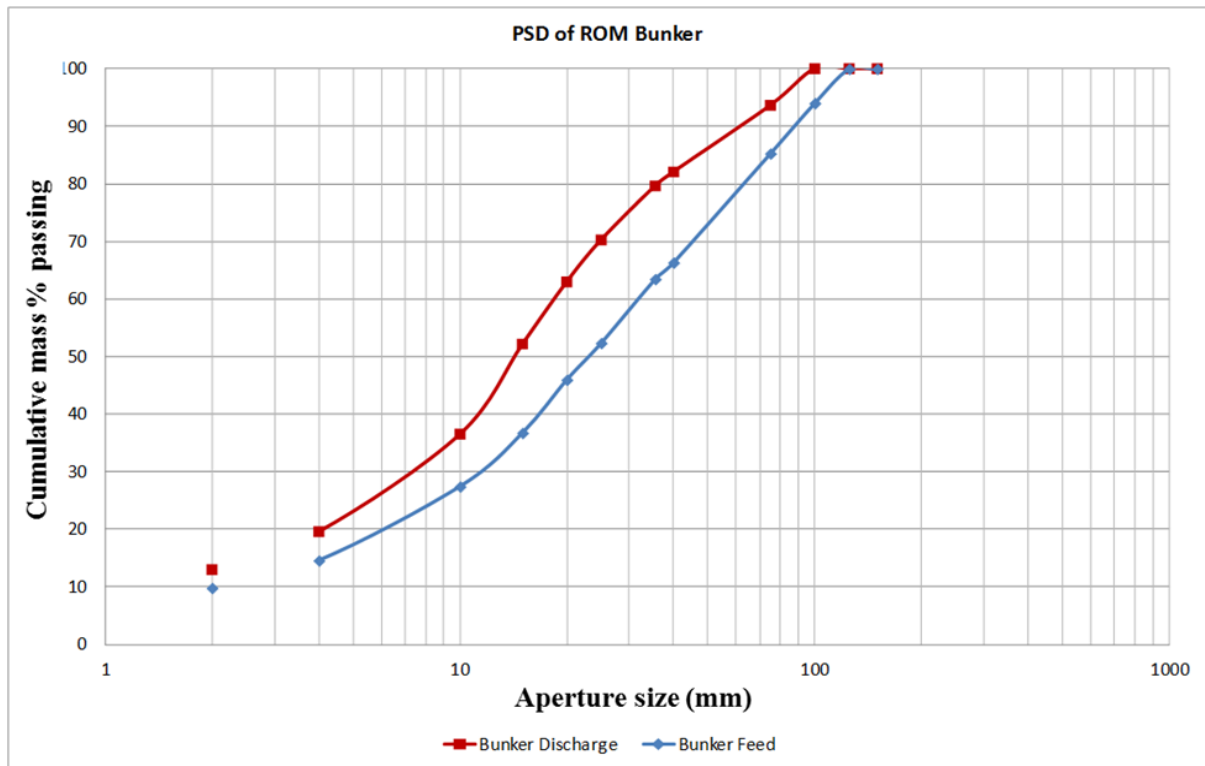


**Figure 3.5b: PSD results for bunker feed and discharge (Sekano 2014)**

## 3.6    PHYSICAL CONDITIONS AT THE STORAGE BUNKER

It was critical to obtain as much information as possible on the physical conditions around the bunker operation. Information was gathered using two methods, namely physical measurements taken on site, and information gained from the local Lephalale weather station. Figure 3.6a shows the type of physical measurements taken around the bunker.
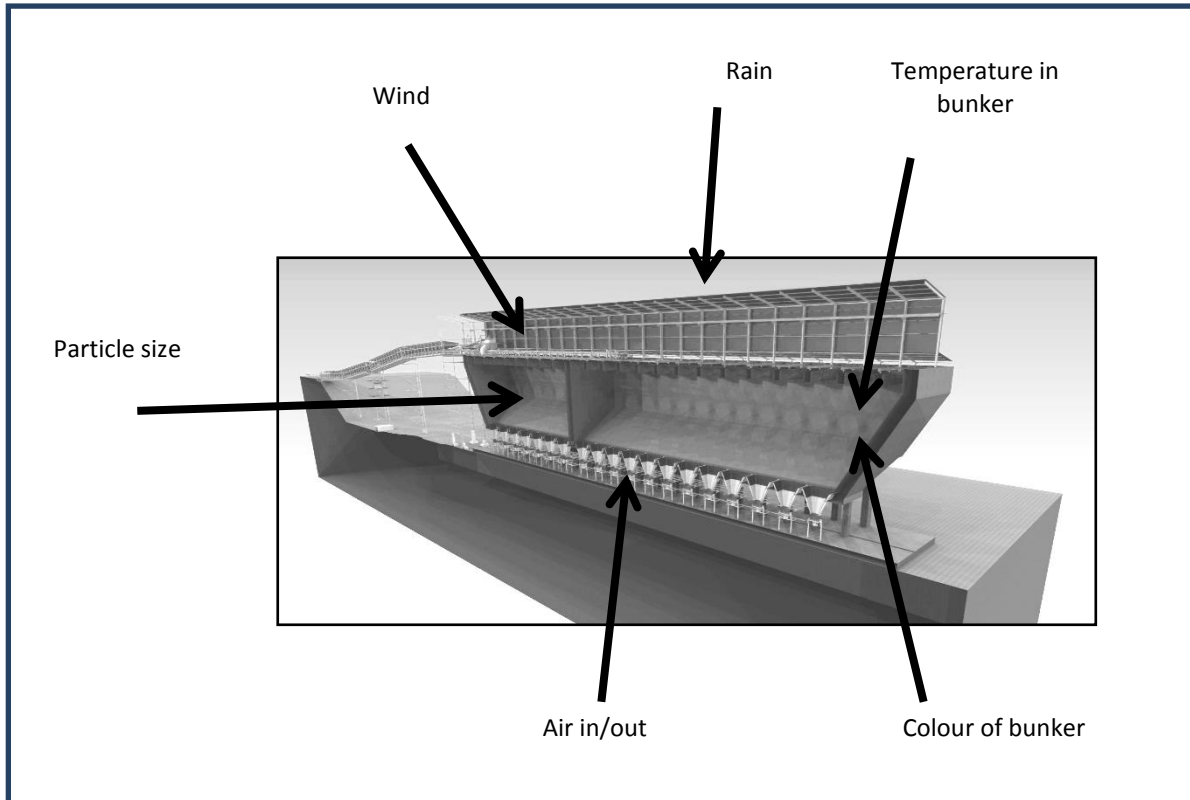
**Figure 3.6a: Raw coal storage bunkers with external factors**

### 3.6.1 Regional climate

Regional information was obtained from various reports on the weather patterns in Limpopo province. This information was used to establish the regional weather patterns relevant to the local area and the wind rose pattern from 2007 to 2009 as per Figure 3.6c. The local weather station was contacted via the Mine's Senior Environmental Specialist to provide the raw data for the full year of 2012. These data were analysed to indicate weather in the months of the year, wind speed, wind direction, temperature, pressure and humidity. The data are presented in Table 3.6a. In was necessary to investigate the wind direction, the rainfall pattern and the moisture content in the air in order to establish how this would affect SC in the bunker during normal operations.

The GG mining operation is situated in the Waterberg region of South Africa, which falls within the subtropical high-pressure belt. The mean circulation of the atmosphere over the subcontinent is anti-cyclonic throughout the year (except for near the surface) (Preston-Whyte & Tyson 1997). The synoptic patterns affecting the typical weather experienced at the Mine

owe their origins to the subtropical, tropical and temperate features of the general atmospheric circulation over southern Africa. The subtropical control is brought about via the semi-permanent presence of the South Indian Anticyclone (HP cell), the Continental High (HP cell) and the South Atlantic Anticyclone (LP cell) in the high-pressure belt located approximately 30°S of the Equator (Preston-Whyte & Tyson 1997). The tropical controls are brought about via tropical easterly flows (LP cells) (from the Equator to the southern mid-latitudes) and the occurrence of the easterly waves and lows (Preston-Whyte & Tyson 1997). The temperature control is brought about by perturbations in the westerly wave, leading to the development of westerly waves and lows (LP cells), i.e. cold fronts from the polar region, moving into the mid-latitudes (Preston-Whyte & Tyson 1997). Seasonal variations in the positioning and intensity of the HP cells determine the extent to which the westerly waves and lows influence the atmosphere over the region. In winter, the high-pressure belt intensifies and moves northwards, while the westerly wave in the form of a succession of cyclones or ridging anti-cyclones move eastwards around the South African coast. The positioning and intensity of these systems are thus able to influence the region's weather significantly.

In summer, the anti-cyclonic HP belt weakens and shifts southwards, thereby weakening the westerly wave. Anti-cyclones (HP cells) are associated with convergence in the upper levels of the troposphere, strong subsidence throughout the troposphere, and divergence near the surface of the earth. Air parcel subsidence, inversions, fine conditions and little to no rainfall occur because of such airflow circulation patterns, i.e. relatively stable atmospheric conditions. These conditions are not favourable for air pollutant dispersion, especially in respect of those emissions close to the ground.

Westerly waves and lows (LP cells) are characterised by surface convergence and upper-level divergence which produce sustained uplift, cloud formation and the potential for precipitation. Cold fronts, which are associated with the westerly waves, occur predominantly during winter and create unstable atmospheric conditions. These unstable atmospheric conditions bring about atmospheric turbulence which creates favourable conditions for air pollutant dispersion. The tropical easterlies and the occurrence of easterly waves and lows affect southern Africa mainly during the summer months. These systems are largely responsible for the summer rainfall pattern and the north-easterly wind component that occurs over the region (Preston-Whyte & Tyson 1997).

Precipitation reduces erosion potential by increasing the moisture content of erodible materials. This represents an effective mechanism in reducing the generation of particulate atmospheric pollutants and is therefore considered during air pollution studies. Precipitation also facilitates the removal of pollutants in the atmosphere through wet deposition and wet depletion.

The lowest rainfall levels are typically experienced in the month of June and the highest levels during January. Rainfall is typically experienced in the form of short-duration intense convection thunderstorms. Droughts are endemic to the more semi-arid and arid regions, while occasional flooding may occur during the summer months from convectional thunderstorms and tropical disturbances (Limpopo State of the Environment Report 2004). Another rainfall station located close to the Mine recorded similar rainfall trends over a monitoring period from 1988 to 2011. The annual rainfall over the monitoring period was 446 mm per annum, with the highest rainfall being experienced in the month of December.

Air temperature is important, both for determining the effect of plume buoyancy (the larger the temperature difference between the plume and the ambient air, the higher the plume is able to rise), and for determining the development of the mixing and inversion layers. The highest temperatures are typically experienced during the summer months of November, December, January, February and March. The lowest temperatures are experienced during the winter months of June, July and August. The annual average temperature for the town of Lephalale (located approximately 18 km to the east of the mine) is 22 °C per annum, with a maximum of 39.4 °C in summer (for the period 1995 to 2005) (Swanepoel 2012). Frost is experienced very seldom in this region.

The GG Mine is located in the summer rainfall region of South Africa and thus receives most of its rainfall during this period. However, inter-annual rainfall variability is clearly shown in the rainfall data from this region (Limpopo State of the Environment Report 2004). The 35-year record of total annual rainfall exhibits an erratic pattern of wet and dry years. The annual rainfall for the town of Lephalale (located approximately 18 km to the east of the Mine) is 393 mm per annum for the period 1995 to 2005 (Limpopo State of the Environment Report 2004).

Table 3.6a shows the summarised information obtained from the Lephalale local weather station for the period January to December 2012. This table also indicates the maximum and minimum temperatures for the months of 2012.

**Table 3.6a: Lephalale local weather station information (Swanepoel 2012)**

| Month | Wind speed Av. wind speed | Wind direction Av. wind direction | Temperature Av. temp | Min. | Medium | Max. | Pressure Av. pressure | Humidity Av. humidity | Min. | Medium | Max. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 1.29 | 89.93 | 26.28 | 17.70 | 25.40 | 38.80 | 917.12 | 56.58 | 16.00 | 57.00 | 93.00 |
| Feb | 1.31 | 73.07 | 27.19 | 18.40 | 26.40 | 38.90 | 917.11 | 52.45 | 13.00 | 52.00 | 96.00 |
| Mar | 1.36 | 81.01 | 25.87 | 15.80 | 24.90 | 39.40 | 918.83 | 46.53 | 10.00 | 43.00 | 92.00 |
| Apr | 1.19 | 74.60 | 21.42 | 10.60 | 20.80 | 34.70 | 923.09 | 46.68 | 10.00 | 47.00 | 89.00 |
| May | 1.02 | 87.34 | 19.10 | 5.60 | 18.55 | 35.00 | 924.67 | 40.49 | 4.00 | 39.00 | 91.00 |
| Jun | 1.19 | 74.60 | 21.42 | 0.20 | 15.20 | 29.50 | 923.09 | 46.68 | 5.00 | 39.00 | 90.00 |
| Jul | 1.19 | 101.53 | 15.64 | 1.70 | 14.80 | 28.80 | 925.46 | 41.94 | 5.00 | 40.00 | 88.00 |
| Aug | 1.55 | 108.94 | 18.39 | 1.70 | 18.00 | 34.60 | 923.61 | 32.15 | 1.00 | 30.00 | 79.00 |
| Sep | 2.12 | 88.14 | 21.95 | 10.60 | 21.35 | 36.00 | 922.32 | 41.27 | 2.00 | 40.00 | 89.00 |
| Oct | 2.07 | 77.06 | 23.91 | 13.70 | 22.90 | 37.90 | 920.15 | 50.22 | 4.00 | 50.00 | 96.00 |
| Nov | 1.81 | 83.57 | 25.25 | 13.60 | 24.90 | 38.50 | 920.24 | 48.45 | 9.00 | 48.00 | 96.00 |
| Dec | 1.46 | 91.98 | 25.15 | 17.30 | 24.10 | 36.20 | 918.66 | 58.91 | 18.00 | 60.00 | 96.00 |
| Av. for year | 1.462 | 85.980 | 22.631 | 0.200 | 22.125 | 39.40 | 921.196 | 46.863 | 1 | 45 | 96 |
| Max. for year | 2.12 | 108.94 | 27.19 | 18.40 | 26.40 | 39.40 | 925.46 | 58.91 | 18.00 | 60.00 | 96.00 |
| Min. for year | 1.02 | 73.07 | 15.64 | 0.20 | 14.80 | 28.80 | 917.11 | 32.15 | 1.00 | 30.00 | 79.00 |

The Chief Mine Surveyor was contacted to establish the layout and direction of the storage bunker. He plotted the direction of the bunker over the layout of the bunker on the physical site as per Figure 3.6b.

He also plotted the most common wind direction at the bunker and this is shown in Figure 3.6c. This information was necessary to understand how the bunker is positioned in relation to the regular wind direction. This would provide valuable information to establish whether air is being forced into the bunker based on the direction of its layout.

Winds at the GG Mine are expected to originate from the east-north-east (24% of the time) and the north-east (20% of the time). Wind speeds are low to moderate, with a low percentage (12.46%) of calm conditions (<1 m/s).
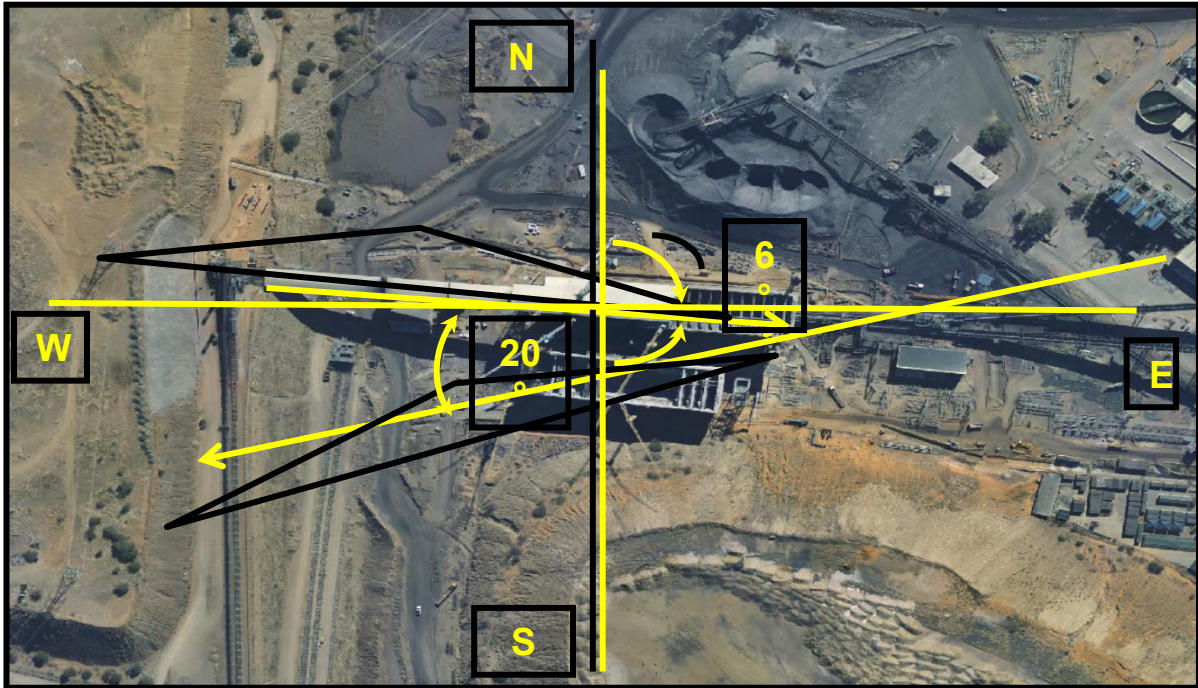
**Figure 3.6b: Storage bunker direction and wind direction (Smith 2014)**
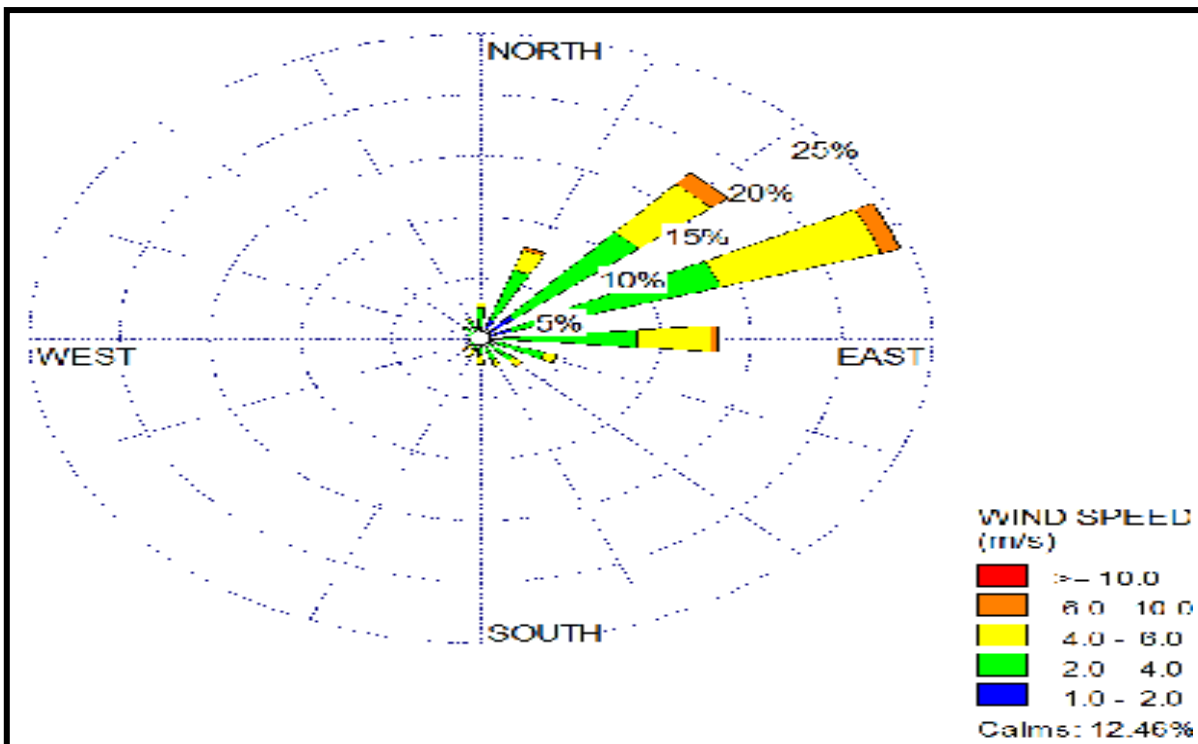


**Figure 3.6c: Modelled GG mine – wind pattern from 2007 to 2009 (Bennett & Schlechter 2012)**

### 3.6.2    Velocity measurements taken at the bunker

Velocity measurements were taken at various points around the bunker with the help of the Mine Hygiene Specialist, who used a well-calibrated air velocity meter and an illumination meter to take measurements at eleven different points around the storage bunker (Kotze 2014). This information was necessary to establish the wind speed around the bunker: whether it was possible that the bunker was drawing in air thereby causing SC; and whether SC was visible to the naked eye.

It was challenging to empty the entire bunker to take measurements because the bunker was in production most of the time. It was only possible to empty one drawdown point over a weekend to take the measurements. The entire bunker operation had to be switched off and the area locked out before any work could take place in that area. The measurements taken are as indicated in Figures 3.6d and 3.6e. A value of 1.27 m³/s was measured at the bottom of the bunker. It was downcast from the bunker chute to the conveyor belt at the bottom. Only "Area 4" was empty and it was difficult to establish whether the overall average airflow would increase or decrease if more compartments were empty. A full record of all measurement points is presented in Table 3.6b.
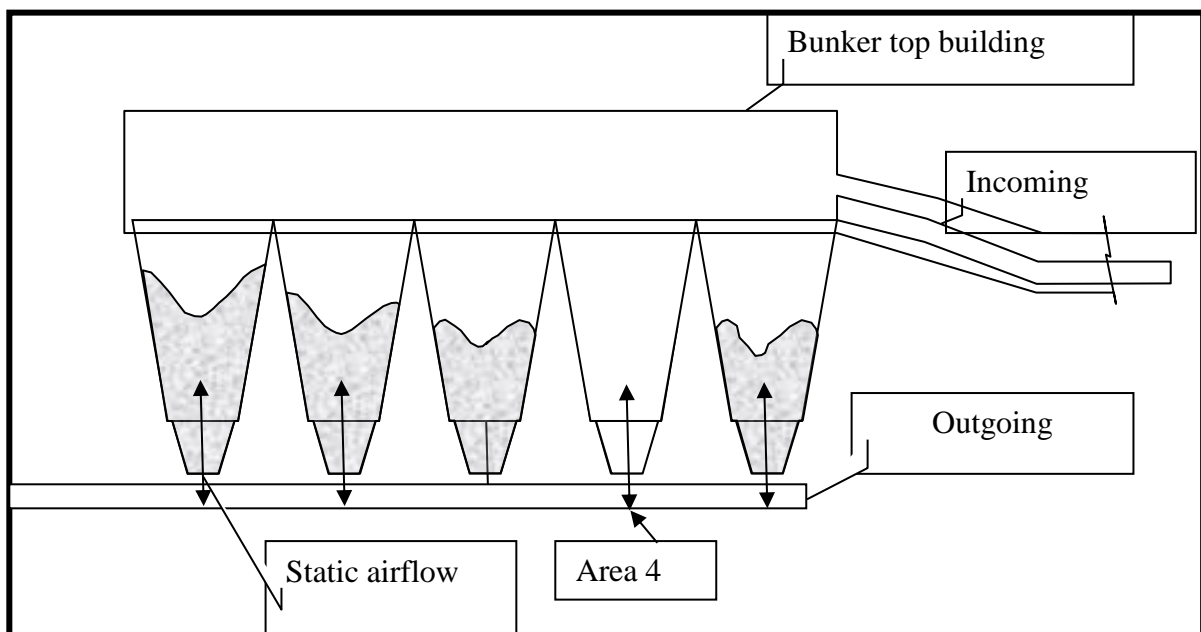


**Figure 3.6d: Storage bunker front view – Measurement points**
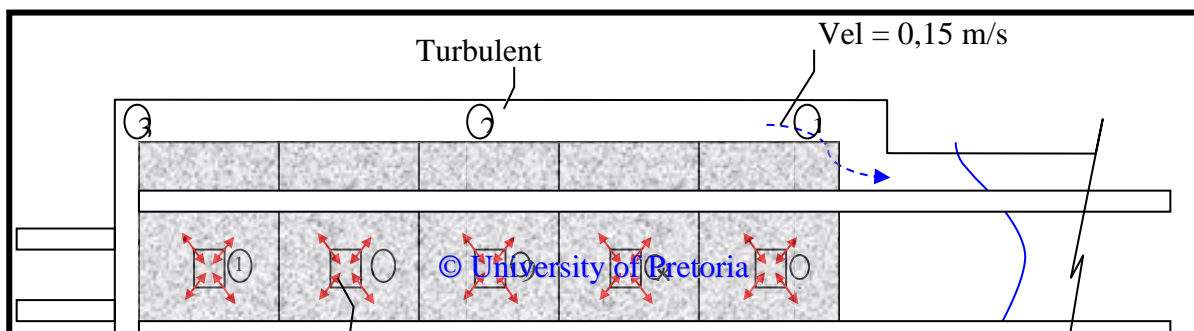
**Figure 3.6e: Storage bunker top view – Measurement points**

**Table 3.6b: On-site measurements at the bunker**

| Position | Temp | Velocity | O$_2$ |
|----------|------|----------|-------|
| 1 | 15.5/19.5 ºC | 0.15 m/s | 21% |
| 2 | 15.5/19.5 ºC | Turbulent | 21% |
| 3 | 15.5/19.5 ºC | Turbulent | 21% |
| 4 | 15.5/19.5 ºC | Turbulent | 21% |
| 5 | 15.5/19.5 ºC | Turbulent | 21% |
| 6 | 15.5/19.5 ºC | Turbulent | 21% |
| 7 | 14.3/19.5 ºC | Static | 21% |
| 8 | 14.3/19.5 ºC | Static | 21% |
| 9 | 14.3/19.5 ºC | Static | 21% |
| 10 | 14.3/19.5 ºC | Static | 21% |
| 11 | 14.3/19.5 ºC | Static | 21% |

The following observations were made when the measurements were being taken on site:

- There was no air transfer from the bottom to the top of the bunker or vice versa. The only time that movement of air occurred was when the compartment at Area 4 was emptied for measuring purposes.
- All the bunker's discharge chutes had coal in them and the level of the coal varied between chutes.
- The incoming conveyor was not operating at the time.
- The top area of the bunker was very dusty.

- At the time the measurements were taken, there was no indication of SC. However, in a few areas, such as in the coal on the extraction conveyor, symptoms of SC were visible.

- It was not possible to get into the bunker to take measurements for safety reasons. The bunker is 22 m in height and filled with coal.

### 3.6.3    Colour of the bunker

The colour of the bunker was obtained from the manufacturing drawings and was confirmed on site as being cement–plastered, with no paint on the outside walls. The internal portion of the bunker was normal cement plaster and towards the bottom of the bunker, the sides were lined with impact steel liners. This information was important to establish whether the bunker was absorbing heat due to its colour and whether it was possible that the temperature inside the bunker was affected by this absorbed heat. For the sake of completeness, it was necessary to rule out all possible causes of SC in this exercise.

### 3.5    CONCLUDING REMARKS

The purpose of the qualitative research was to gain insight into the practical and academic experience of learned experts in the field of SC. The literature review provided the basis for the understanding of SC and this was augmented by the inputs provided by the interviewees on the bunker design and possible solutions to the SC problem.

The inputs from the literature study, the interviews, the field research and data collection were collated and are presented in this chapter.

The results indicated that a low-grade, medium-rank coal is being supplied to the bunker. The sulphur range is not stable across the ore body and in some areas can be high. The coal being supplied to the bunker has a high reactivity ratio due to its vitrinite content.

The results showed that the current mining practice allows coal to stand on the benches for various periods of time (2 weeks on average), irrespective of the changes in the influencing factors, such as changes in coal properties, inadequate loading practices, rain exposure and high environmental temperatures.

The SC situation in the bunker can be affected by the physical factors such as the fines ratio, high temperatures in and around the bunker, dead spots in the bunker structure and the temperature of the coal entering the bunker. These results were based on quantified values for the fines ratio, temperature and coal entering the bunker. The dead spots were visual observations from the drawings and construction information obtained.

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# CHAPTER 4
# ANALYSIS AND EVALUATION OF RESULTS

## 4.1    INTRODUCTION

In this chapter, the results of the study are discussed in relation to the literature review. Recommendations arising from the research are in Chapter 6. The following aspects are discussed: the type of coal supplied to the bunker; factors relating to the current mining practice; and physical factors around the bunker.

## 4.2    TYPE OF COAL SUPPLIED TO THE BUNKER

This section addresses the importance of the type of coal that is being stored in the bunker and how it is processed prior to storage. This will provide valuable information to ascertain whether the coal self-ignites before being stored in the bunker.

### 4.2.1    The GG ore body and grade

The geological setting of the GG ore body (as was shown in Figure 1.1b) is fault bounded along the southern and northern margins. The Daarby fault is close to the current mining area (Faure *et al.* 1996). According to Kaymakci and Didari (2002), faulting and faulted zones could contribute to the dangers of SC by allowing air ingress into the coal mass. The US Department of Energy (1994) claims that in opencast mines, the main factors responsible for mine bench fires due to SC are the presence of micro- and macro-cracks in the bench walls, which allow the entry of air, extended exposure of the bench walls to the open atmosphere, and accumulation of loose coal on the bench floor.

As was shown in Table 1.1a, the lithology indicates the impurities in the different zones. These impurities were reflected in Table 3.4a as the grade of the coal. The grade of the coal being fed to the bunker ranges from a very low to a Carbonaceous-grade coal. The ash content, which is an important component in determining the grade, has a range from 31-55%.

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This is supported by the findings of Kaymakci and Didari (2002),who claimed that high-grade coals have a lower tendency to self-heat, while the low-grade coals have a higher tendency to self-heat. The ash content decreases the propensity of a coal to heat spontaneously. However, certain constituents of the ash (lime, soda and iron compounds), may lead to the acceleration of heating, whereas other constituents (alumina and silica) could have a retarding effect. Therefore, some components of ash promote combustion, while others inhibit its development. According to the US Department of Energy (1994), the lower the ash-free calorific value, the greater the heating tendency.

## 4.2.2    Rank

As was shown in Table 3.4a, the rank of the coal at the Mine ranged from a meta-lignite, which is a very low-rank coal, to a para-bituminous medium-rank coal. Since the vitrinite reflectance is a direct measure of the rank of the coal, petrographic analysis is important in order to understand the maceral composition. As was shown in Table 3.4b,the vitrinite and exinite values decrease from the top bench B2 in the ore body to the lower bench B9A with a range of 74.52–5.01%. The inertinite increases from bench B2 to bench B9A with a range of 5.51– 60.16%. This means that for this orebody, the coking properties are much greater on the top benches and decrease towards the lower benches due to the higher amount of vitrinite in the upper benches. The exinite consists of coats, leaf cuticles, waxes and resins. On its own, exinite is non-coking but it does help the coking properties of vitrinite (England *et al.* 2002). Inertinite has no coking properties and if it is present in high concentrations, it nullifies the coking properties. However, it does have a lower volatile content than vitrinite.

Phillips *et al.* (2011) found that the rank of coal is one of the chemical factors that contributes to SC. Kaymakci and Didari (2002) state that it is widely recognised in the coal industry that lower-ranking coals are more susceptible to SC than higher-ranking coals. According to Adamski (2003), as the rank decreases towards lignite, the tendency for coal to self-heat increases, i.e. the lowest-ranked coal is more likely to self-heat under the same set of conditions. The rank, combined with the inherent reactivity of the coal's particle size, results in an overall oxidation reactivity for the coal that could be regarded as or termed the "pile oxidation reactivity".

### 4.2.3    Sulphur content

As was mentioned before in Chapter 3, Table 3.4a, the average sulphur values differ from bench to bench. They range from 0.862–2.53% from Bench B2 to B9A. On each bench the values change from a minimum value of 0.257% to a maximum value of 5.325%. The sulphur values are not constant on any of the coal benches.

Phillips *et al.* (2011) suggested that organic sulphur and the presence of pyrites as chemical factors contribute to SC. Kaymakci and Didari (2002) explain how the chemical factors such as pyrite content may accelerate SC. According to Panigrahi *et al.* (2005), at one mine coal having a sulphur content of 0,5% started to burn within two weeks of exposure. Guney (1968) concluded that the pyrite content also contained sulphur minerals, which may accelerate spontaneous heating. The pyrite in the coal must be present in a concentration greater than 2% before it can have any effect. However, according to the US Department of Energy (1994), the sulphur content is a minor factor in the spontaneous heating of coal. It is possible that the US Department of Energy has placed a higher weighting on elements other than sulphur, thereby rating sulphur as playing a minor role in spontaneous heating.

In summary, it can be stated that at times the coal being supplied to the bunker is exposed to faulting and fault zones at the mine, which increase air ingress, and invariably lead to SC. The ash values for the GG coal are high and it is a lower-grade coal, and for this reason it is prone to SC. This is further dependent on the coal bench being mined and the amount of lime, soda and iron content in the ash. The rank of coal is low for the GG orebody and, as stated previously, the lower the rank of the coal, the greater its tendency to SC. The sulphur content of the orebody is high and at times (depending on the location of mining in the orebody) it could give rise to SC due to this high sulphur content.

### 4.3    CURRENT MINING PRACTICE

The current mining practice at GG is to drill, blast, stockpile, load and haul coal. The coal stockpile stands on the mining benches in LCM for the duration, as was shown in Table 3.5. Loose material standing on the mining benches is exposed to various environmental influences, such as air ingress, which cause oxidation and then lead to heating. It has been established that

in order for the coal to self-ignite it must exhibit thermal properties and a high temperature must be reached rapidly up to a critical point.

The average standing time of material being supplied to plants GG8 and GG2 is about two weeks. This coal is highly reactive as the vitrinite and exinite contents are high. It is a carbonaceous rock-grade coal that has a high ash content ranging from 43-55%. The sulphur content is high, with a range from 0.862–1.795%.

The average standing time of material being supplied to plants GG3 and GG7 is about six days. This coal is less reactive than the coal supplied from the upper benches. The vitrinite and exinite contents range from 5.01–21.42%. It is a very low grade coal with an ash content ranging from 31–34%. The average sulphur content is higher than the coal in the top benches, with a range of 2.0–2.53%.

Phillips *et al.* (2011) claim that many factors in both surface and underground mining contribute to the potential SC of coal, such as inadequate loading of coal, cleaning techniques, poor housekeeping, blasted material being stored too long before loading, the stockpiling of coal, excavation stability and maintenance.

According to De Korte (2014), the time taken for heating to occur varies considerably. Product stockpiles and coal inventory in the mine should not be left longer than the incipient heating period. Both ROM and saleable product coal have been known to be susceptible to SC. A layer of coarse particles at the base and edges of the stockpile may result in increased ventilation passing through the coal. The situation is exacerbated by prevailing hot, moist winds, which may lead to a greater risk of SC in the summer months.

The US Department of Energy (1994), Adamski (2003), Phillips *et al.* (2011) and Humphreys (2004) made similar claims that freshly extracted coal absorbs oxygen more quickly than coal mined at an earlier time. Coal that has been exposed to oxygen for longer periods (and freshly extracted) is more likely to heat spontaneously if mixed. The oxygen absorption rate is a function of the coal's age and fresh coal is more reactive than aged coal or coal that has been exposed to oxygen for longer periods. The reactivity depletes with exposure and oxidation over time. In the opinion of the US Department of Energy (1994), hot spots may not be prevalent

for the first one to two months. The heat transfer within the pile is controlled largely by the airflow through the coal, and will be less significant at very low flow rates than at higher flow rates. The surface temperature of the pile controls the convective heat loss at the pile's surface. These heat transfer processes are dependent on the temperature distribution and geometry of the reacting coal pile.

Phillips *et al.* (2011) allege that when rainfall causes erosion at the coal piles, it exposes more coal to oxygen in the atmosphere and, depending on the properties of the coal, heating of broken coal left in stockpiles in the pit or elsewhere on the mine can occur after a period of time.

Kaymakci and Didari (2002) concluded that the moisture content, i.e. the drying and wetting of coal, has an influence on the propensity of coal to self-heat, whereas Lyman and Volkmer (2001) established that the wetting and drying of coal provides an opportunity for heat transfer to occur in coal stockpiles. The drying of coal is an endothermic process (requires heat) which will affect the heat balance in an oxidising pile of coal. The effect of drying will be to decrease the heat available, resulting in self-cooling. The wetting of coal gives off heat and is an exothermic process, which accelerates self-heating. During the wetting and drying of coal, heat is transferred between the coal and the air. Conductive heat transfer takes place through the coal and at the surface of the coal pile. The presence of moisture can alter the inherent rate of oxidation. According to Lyman and Volkmer (2001), increases or decreases in heat affect the moisture content and oxidation rates, which explains most of the heat generated in the coal.

Adamski (2003) and Grossman *et al.* (1995) drew similar conclusions, namely that where oxygen makes contact with the coal and an oxidation process starts to produce heat, and if this heat cannot dissipate, SC starts to occur. Extra heat due to the condensation of moisture can lead to unstoppable self-heating if a coal pile is at a critical temperature point and oxygen is available. If the heat is dissipated, the temperature of the coal will not increase. However, if the heat is not dissipated, the temperature of the coal will increase. They also claim that the higher the temperature, the faster the coal reacts with oxygen. If the stockpile temperature increases above 30 °C, then vaporisation of the moisture content of the coal takes place, as well as the emission of carbon dioxide and hydrocarbons of lower molecular weight. The vaporisation and emission rates of gases increase with temperature. These products decrease the ignition point of the coal. The autogenous heating of stockpile coal is restricted to small

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distinct areas, referred to as hot spots, which are characterised by good oxygen diffusion and insufficient heat transfer. The oxidation-induced autogenous heating of coal causes a loss in calorific value of the reacted coal and therefore causes safety and handling problems. In the lower temperature range, only a small portion ($< 25\%$) of the oxygen consumed is emitted as gases.

There is overwhelming evidence suggesting that coal stockpiles should not be left on the mining benches for longer than is necessary. The mixing of freshly mined coal and aged coal should be prevented in order to minimise spontaneous heating. The wetting and drying of coal, together with the presence of moisture, is important in the GG mining area because of the high temperatures in the day and the low temperatures at night, especially in the winter months of June, July and August when the temperature fluctuates from 34–1.7 °C. This can affect the oxidation rates and could generate heat in the stockpiles.

It is important to note that any oxygen ingress into the stockpile will lead to oxidation. This oxidation creates heat and increases the temperature of the stockpile. Once the temperature of the stockpile is increased, it induces evaporation and pyrolysis takes place. The pyrolysis process creates hydrocarbons and carbon monoxide while the evaporation causes moisture to be given off.

## 4.4    PHYSICAL FACTORS AROUND THE BUNKER

### 4.4.1    The regional climate

As was shown in Table 3.6a, the average wind speed at the Mine is 1.46 m/s, with a range from 1.02–2.12 m/s. On average, the wind direction is 85.98° NE, with 0° being north. The range of the wind direction is 73.07°NE to 108.94°SE. The average atmospheric temperature is 22.63 °C. The lowest temperatures are experienced in the winter months of June and July. The maximum average temperature is approximately 29.5 °C. During the rest of the months, the maximum temperature ranges from 34.6–39.4 °C. The average humidity is 46.86 and it ranges between 32.15 and 58.91.

The relevant literature indicates that environmental elements, such as wind direction, rainfall patterns and moisture content in the air, contribute significantly to SC of coal stockpiles on the

benches. According to Preston-Whyte and Tyson (1997), the Lephalale area has a weather pattern that witnesses most of its rainfall in the summer months of December, January and February. Occasional flooding may occur during the summer months from convectional thunderstorms and tropical disturbances (Limpopo State of the Environment Report 2004). A rainfall station located close to the mine displayed similar patterns during 1988 to 2011. However, inter-annual rainfall variability is clearly shown in the rainfall data from this region (Limpopo SOE, 2004). The 35-year record of total annual rainfall exhibits an erratic pattern of wet and dry years.

As stated before in this section, the annual average temperature recorded for Lephalale was 22 °C per annum for the period 1995–2005. The highest temperatures are experienced during the summer months of December, January, February and the lowest during the winter months of June, July and August. Frost is very seldom experienced in this region (Limpopo SOE 2004).

## 4.4.2    Layout of the bunker

According to Smith(2014), the bunker layout on the mine is in a 96°NE direction. The wind direction is 70° NE for 24% of the time and 40°NE for 20% of the time (Bennett & Schlechter 2012). This information indicates that for 95% of the time, the wind is not directly in line with the bunker outlet chute, but is blowing onto the corner walls of the bunker or other areas around the bunker. The wind is in line with the bunker outlet chute for only 5% of the time and during those periods, the wind speed is around 2–4 m/s.

The velocity measurements at the bunker indicated that there was no air entry into the bunker. The measurements at points 7–11 indicated static conditions as was shown in Chapter 3, Table 3.6b. Around the top of the bunker, points 1–6, the air was turbulent and only at point 1 was 0.15 m/s recorded. At the bottom of the bunker chute (when there was material present), the velocity meter reading showed static conditions. However, when one of the chutes was empty an airflow of 1.27 m/s was measured at the bottom of the bunker. It was downcast from the bunker chute to the conveyor belt. The ambient temperature was measured at 15.5–19.5°C on the day of the measurements.

## 4.4.3    Degradation of material through the bunker

It has been established that the material entering and exiting the bunker tends to increase the amount of fine coal particles it contains by 5.2% of the –4 mm material. The height of the bunker, which is 22 m, had an impact on the size of coal being supplied out of the bunker. The fines ratio changed from 14.8% to 20% as indicated by Sekano (2014). This increase in fines resulted in downstream processing problems. According to Itay *et al*. (1989), the most important factor contributing to SC is particle size. Very fine coal does not burn due to a shortage of oxygen. Coarse coal burns and is very reactive. The most dangerous combination is a mixture of fine and coarse materials. However, the findings have indicated that a reasonable proportion of fine and coarse coal particles minimise the flow of air entering into the bunker.

In order to appreciate the effect of the porosity between the coal particles, one could take as an illustrative example a set of marbles stacked on top of each other in columns (Figure 4.4). Glover (2015) claims that the grain packing calculation on the left in Figure 4.4 shows a porosity of 47.6%. If the same marbles are packed in the closest possible arrangement, where the upper marble is seated in the valley between the four lower marbles in a rhombohedral packing arrangement, the porosity is reduced to 25.9%. Again, changing the size of the marbles will not change the porosity as long as all the marbles are the same size. However, mixing the sizes of the marbles will create lower porosity, since small marbles can fit in the spaces created between the larger marbles.

It is evident from the airflow measurements that the increase in fine coal particles during their passage through the bunker and their combination with larger coal particles close the gaps and stop airflow through the coal. This is important in ensuring that no oxygen enters the bunker and creates oxidation. However, this increase in fines seem to cause downstream processing problems. Therefore, it can be concluded that a proportion of >20% of fine particles of –4 mm in a bunker will prevent airflow through the coal.



Cubic packing (48% porosity)    Rhombohedral packing (26% porosity)
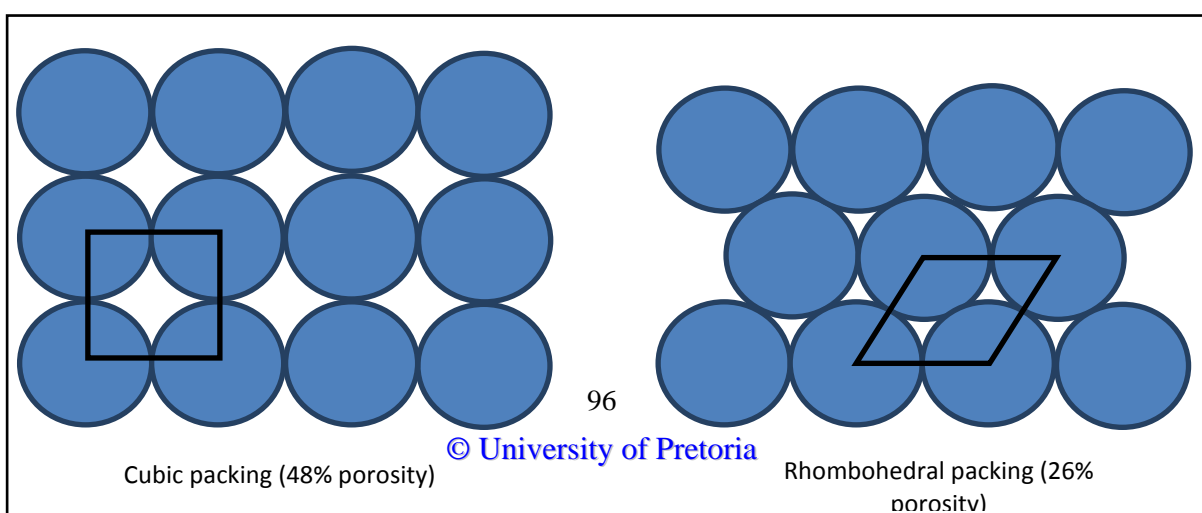
**Figure 4.4: Grain packing of similar size particles (Glover 2015)**

## 4.4.4    Temperature of the coal entering the bunker

The data from the local weather station (see Chapter 3, Table 3.6a) showed that a maximum temperature of 39.4 °C was reached in the summer months of 2012. However, according to the physical thermographic measurements taken, the actual maximum temperature in the mine showed an increase of 30 °C above the temperature indicated by the local weather station data. Therefore, it can be deduced that there is a difference between the temperature given by the local weather station and that which was taken in the pit itself. It was further observed that there is a potential for material that has exceeded the critical temperature point in terms of the R70 test advocated by Humphreys (2004) to enter the bunker. This could be due to the mining practices mentioned earlier or the climate conditions at the mine.

## 4.4.5    Bunker structure

The bunker has "dead spots", which could result in coal standing and oxidising at these points, thereby creating hot spots, resulting in spontaneous combustion. The hot spots in the bunker could damage the civil structure. It must be mentioned that the coal capacity of the bunker when full is 48 000 tons. This excludes its own weight and auxiliary equipment.

In summary, the climate conditions around the mine, in particular the daily temperatures and the weather patterns, have an influence on the actual temperature of the coal entering the bunker and how it oxidises. The temperature of the coal on an average day at the GG Mine could be >45 °C depending on the atmospheric temperature, standing time on the mining bench, its exposure to oxidation and heating, and its chemical composition. It was noted that there is a difference of 30 °C between the Lephalale weather station data and the temperature at the mine. These are some of the factors found during the investigation that influence the temperature of the coal being fed into the bunker.

The bunker layout seems to be well positioned with 95% of the wind direction being out of line with the bunker outlet chutes. The fine particles generated in the bunker appear to assist in preventing air ingress into the bunker. It is important to prevent SC in the bunker and this can only be done by ensuring that the material entering it is not excessively hot and that the coal does not stagnate in the bunker and thus create hot spots. Monitoring equipment in and around the bunker is critically important.

## 4.5    DECISION ANALYSER

The information contained in this chapter was used to create a decision tree, which would assist mine personnel in understanding the origins of the SC problem. A simple plan view of the mine is shown in Figure 4.5a. This figure shows the pit layout, the loading area, the crushers and the storage bunker. At the crusher, if coal is detected as being hot, it is rerouted to the hot coal stockpile for cooling and disposal.
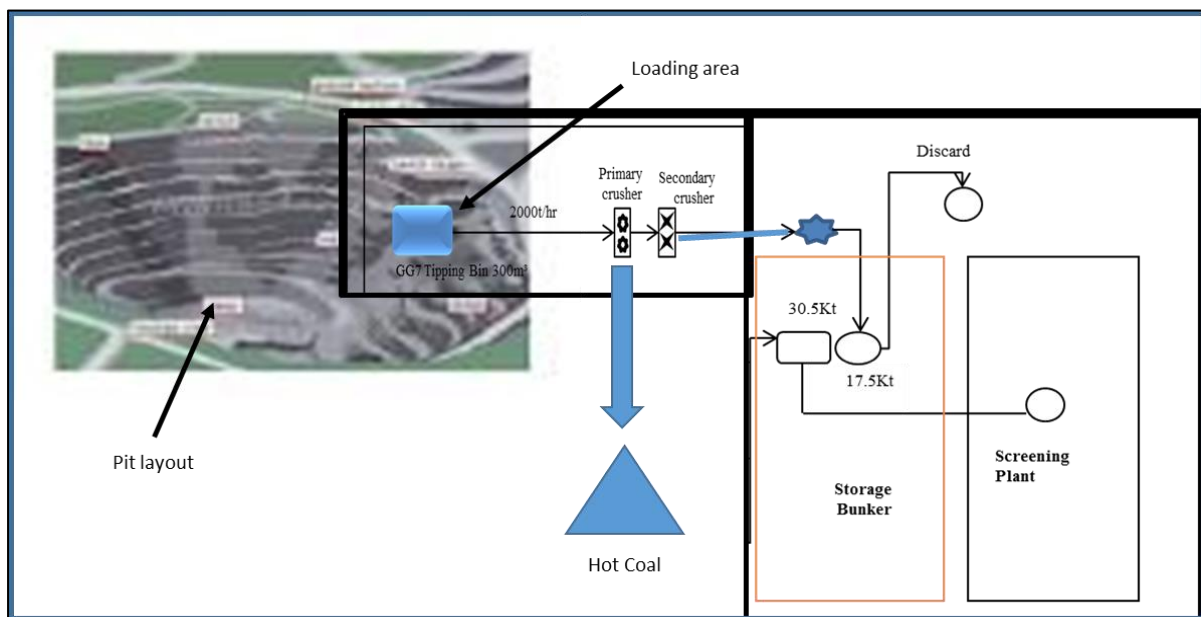


**Figure 4.5a: Plan view of coal moving from the mine to the bunker**

**Step 1: Determine the impact of faulting and fault zones**

The decision process starts at the coal ore body once the material has been blasted as per Figure 4.5b. It is important to establish whether blasted material is lying on a fault or in a fault zone that could allow air ingress into the blasted stockpile. If the answer to this question is "no", normal mining operations should continue using the mine's standards and procedures. If the

answer to the question is "yes", then SC is possible if air enters the stockpile and causes oxidation, which leads to heating. The standing time of the coal on the mine bench must be minimised, and the coal should be moved or processed as soon as possible.
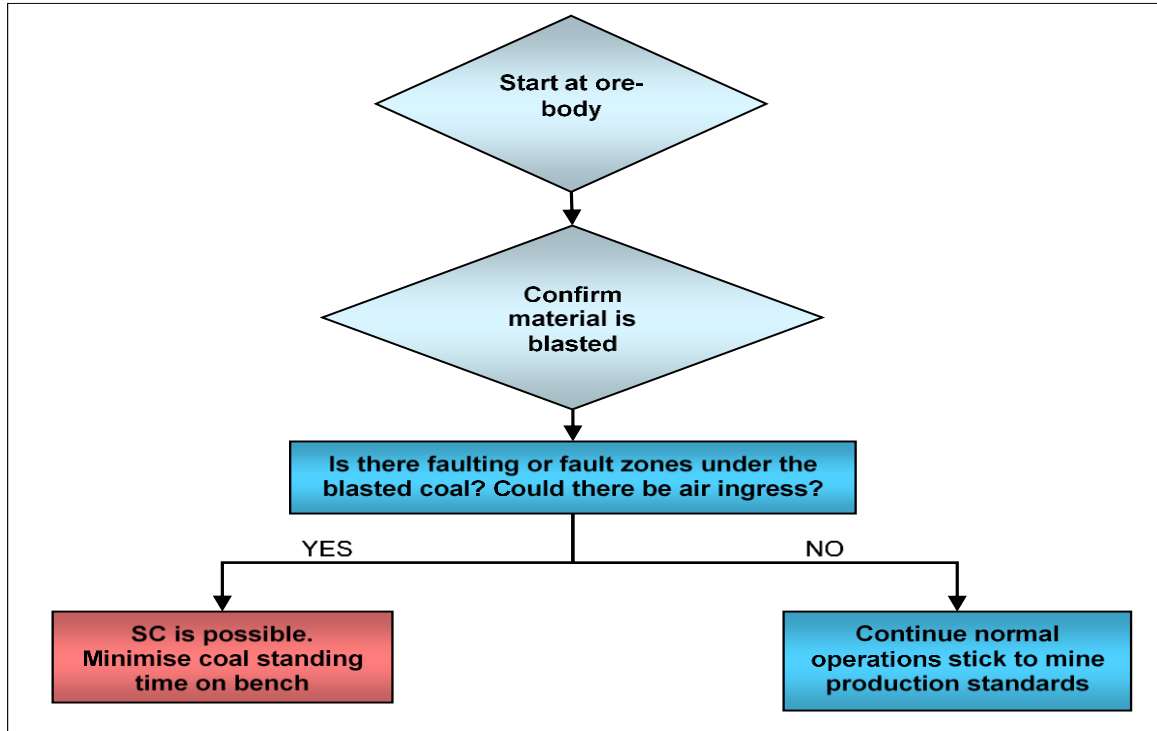


**Figure 4.5b: Impact of faulting and fault zones**

## Step 2: Confirm the grade of coal

This step deals with understanding the impact of coal properties on SC. It starts with understanding the grade of coal present, as per Figure 4.5c. The grade of coal is established by the amount of ash present. A high ash content will give you a low-grade coal, whereas a low ash content will give you a high-grade coal. Once the grade has been established, the heat accelerators must be confirmed. If the ash contains a high amount of lime, soda or iron, then SC is possible. If the ash contains high amounts of alumina or silica, then there is a low possibility of SC. Once it has been established that SC is possible, measures must be put in place to manage the risk and monitor the coal temperature in the operations. These measures could include reducing the standing time of coal on the benches or ensuring that heat is dissipated from the stockpile.
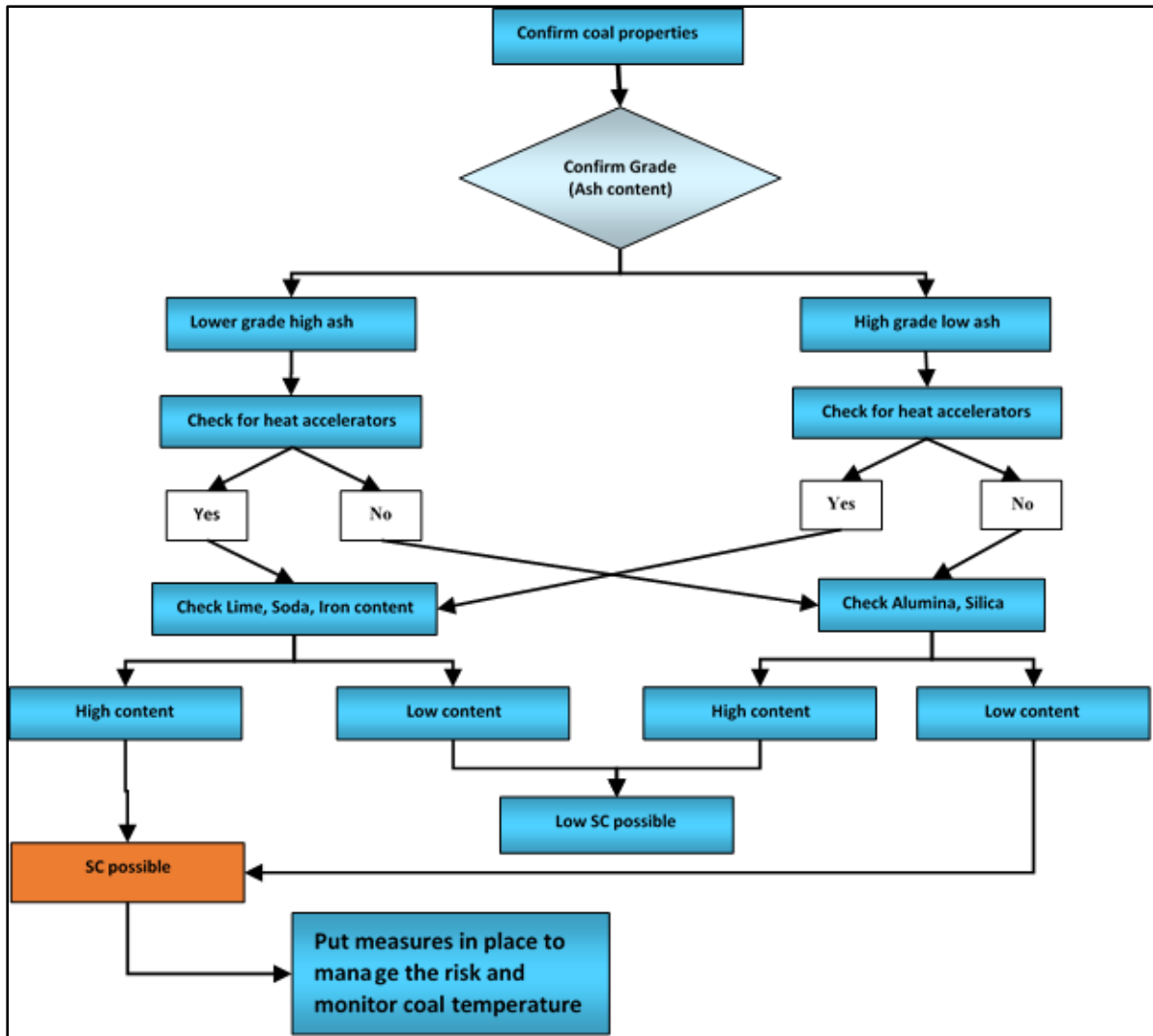
**Figure 4.5c: Confirm grade of coal**

## Step 3: Confirm the reactivity and rank of the coal

The next step is to understand the reactivity of the coal since the reactivity is a direct measure of the rank. A high amount of vitrinite and exinite results in a low percentage of maceral composition, while a low amount of vitrinite and exinite results in a high percentage of maceral composition, as per Figure 4.5d. A high amount of vitrinite and exinite results in higher reactivity, which increases the oxidation rate and results in heating of the coal. A low-rank coal is more prone to SC than a high-rank coal. Once it has been established that SC is possible, measures must be put in place to manage the risk and monitor the coal temperature.
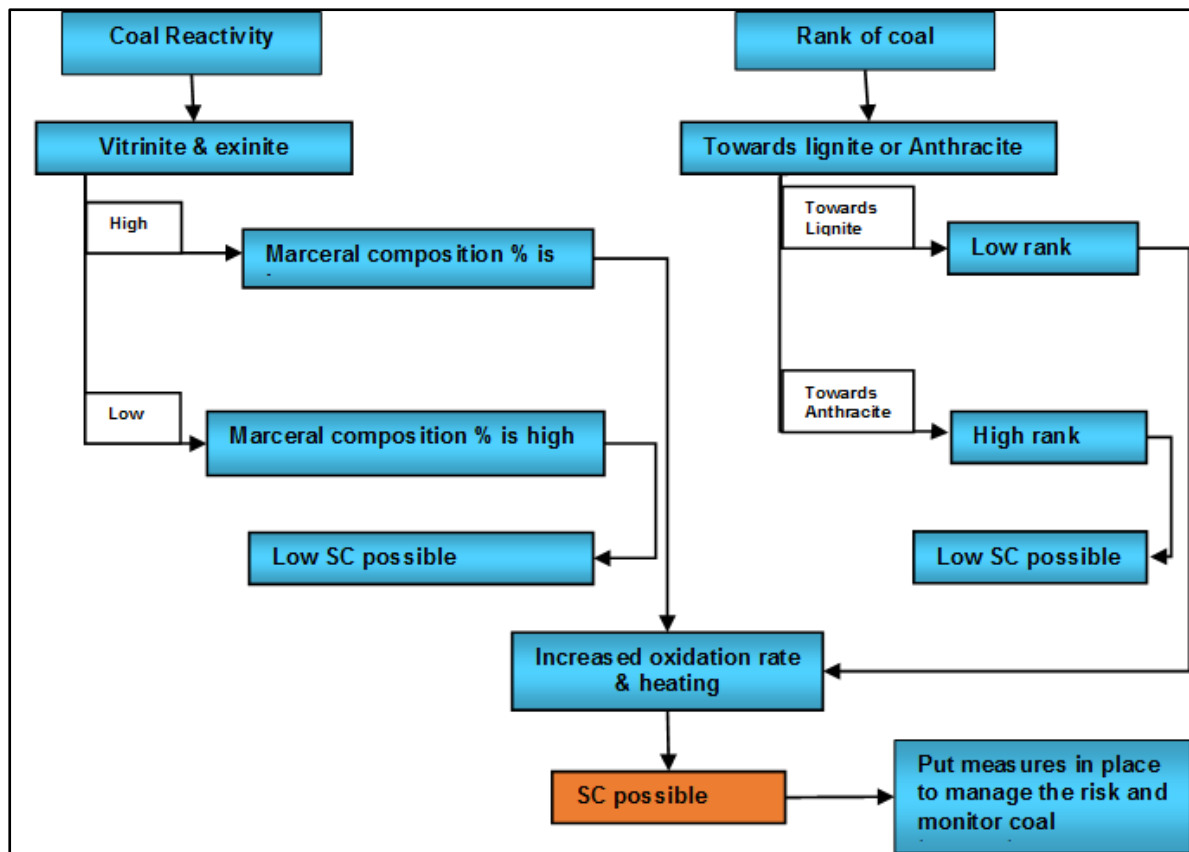
**Figure 4.5d: Confirm reactivity and rank of coal**

## Step 4: Confirm the sulphur content of the coal

In this step the chemical properties must be confirmed, especially the sulphur content. The amount of organic and pyritic sulphur in the coal has an influence on SC, as per Figure 4.5e. High amounts of organic and pyritic sulphur result in a greater possibility of SC, whereas if the organic and pyritic sulphur content is low, the possibility of SC is not so great. If there is a possibility of SC, measures must be put in place to manage the risk and monitor the coal temperature.
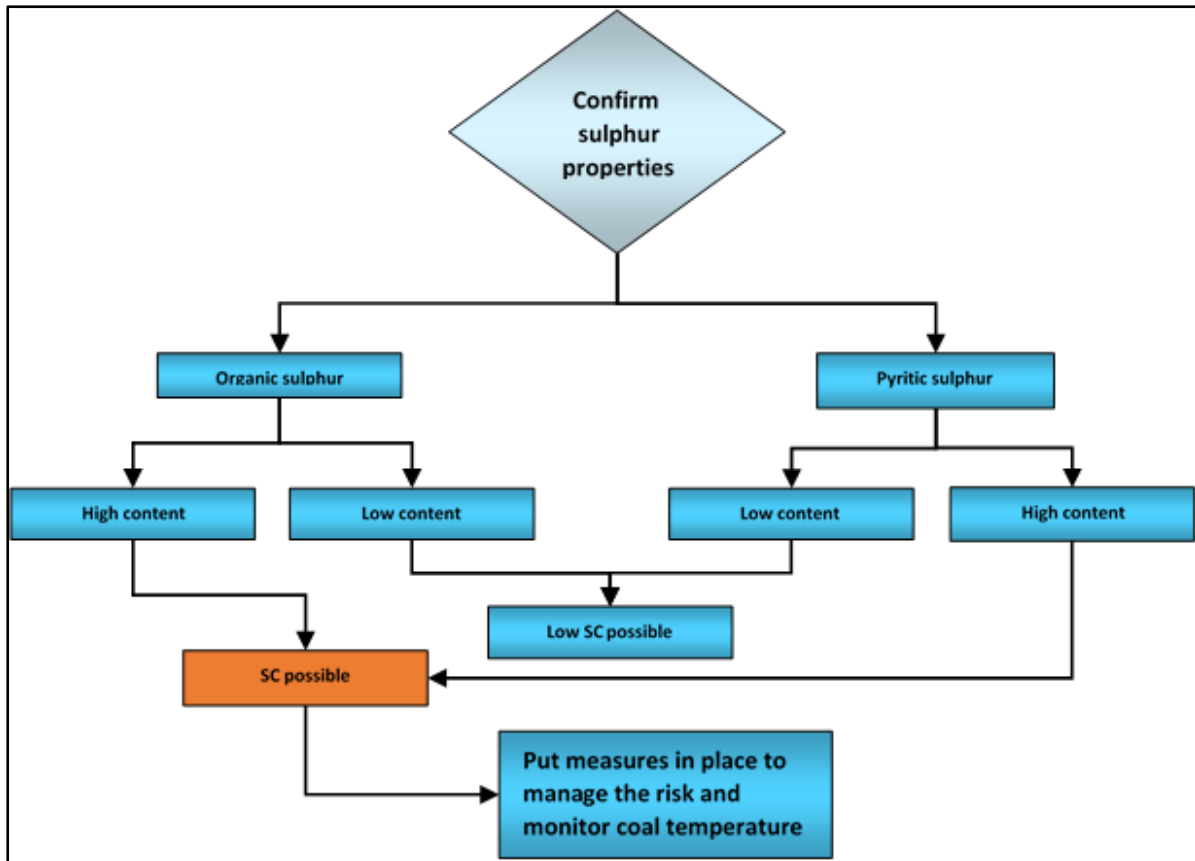
**Figure 4.5e: Impact of sulphur content of the coal**

## Step 5: Determine the coal standing time on benches

To determine the coal standing time on the benches it is important to consider the outcomes from steps 1, 2, 3 and 4. These outcomes, together with other influencing factors such as inadequate loading, poor cleaning techniques, coarse coal at the base of the stockpile, exposure of coal after a rain downpour, the wetting of coal and a high environmental temperature, as per Figure 4.5f, will indicate whether SC is possible. The first priority is to put measures in place to prevent SC. Thereafter measures must be put in place to manage the risk at the source and to monitor the coal temperature regularly.
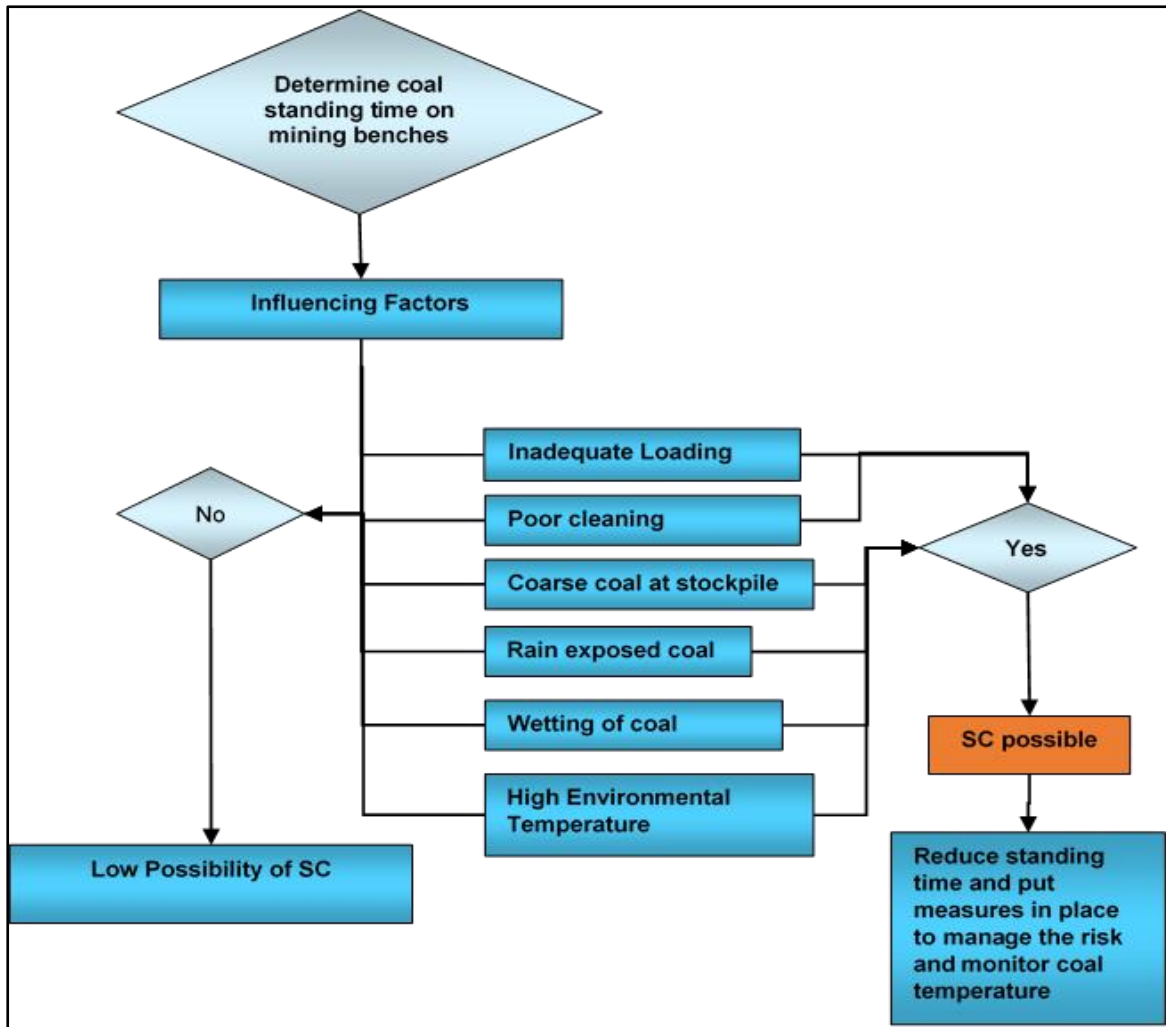
**Figure 4.5f: Determine coal standing time on benches**

## Step 6: Impact of physical factors at the bunker

The last step in this decision process relates to where the coal has been loaded and is being transported to the bunker. If the coal has been loaded into the crusher and the monitoring equipment records a high temperature, then the coal must be redirected to a hot coal area or lay-down area for cooling and disposal, as per Figure 4.5a. Such coal should not be transported to the bunker. This should be the first line of defence in order to prevent hot coal from entering the bunker. At the bunker, as per Figure 4.5g, continuous monitoring is necessary for high-temperature areas. The following have to be checked: air ingress into the bunker, the fines content, and dead spots that could lead to hot spots. If SC is detected in the bunker, the only option available is to stop production and empty the affected coal area immediately.
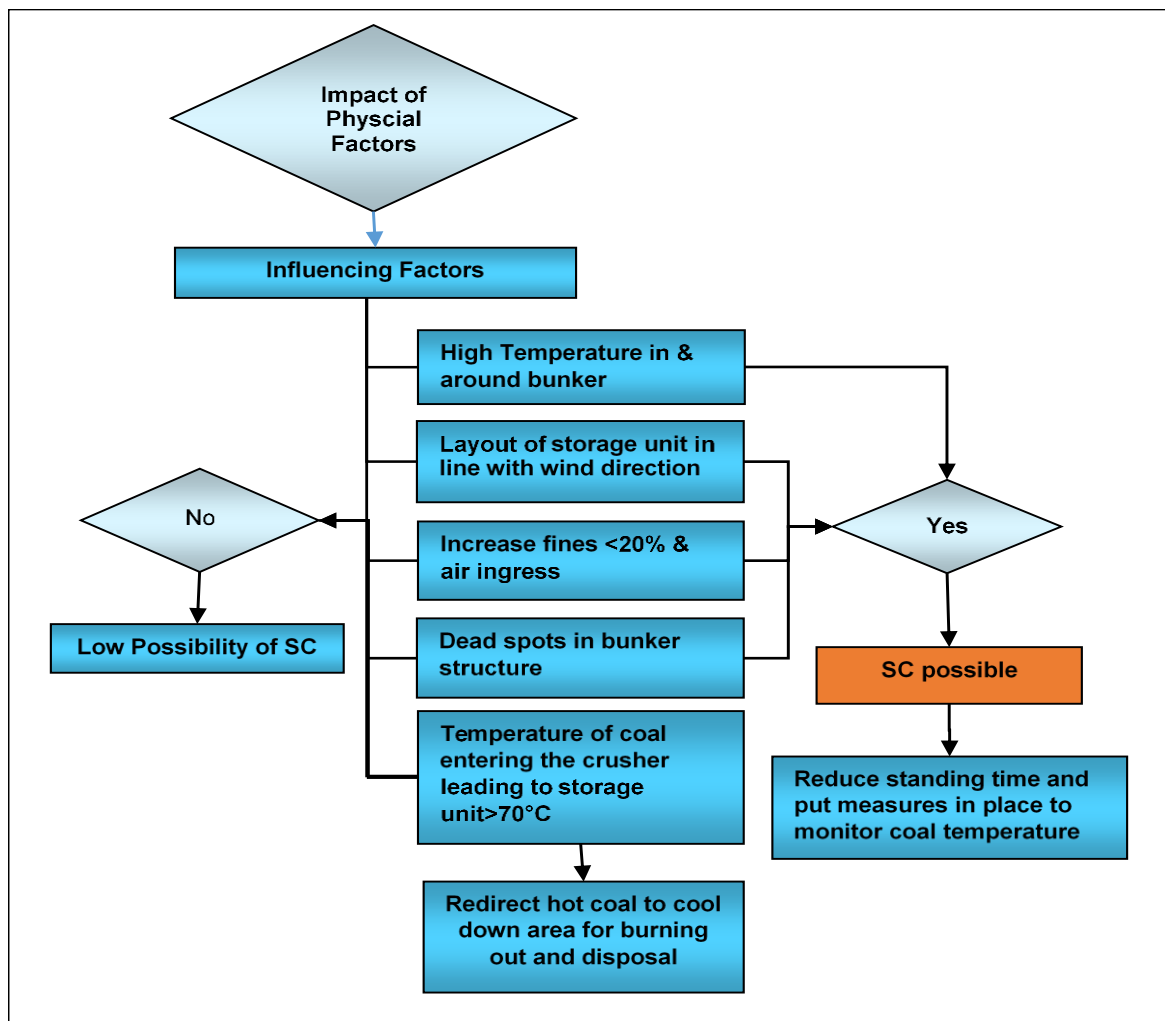
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**Figure 4.5g: Impact of physical factors at the bunker**

## 4.6    CONCLUSION

This chapter provided insight into the factors that could influence SC of coal from the mine (pit) to the storage bunker. It is evident that at the GG Mine, the type of coal and the mining practice play a major role in SC. The physical factors pertaining to the bunker, although minimal, also influence whether or not SC occurs in the bunker. These findings, together with the systematic decision-making guide above, could assist the mine personnel to take early preventative steps to manage the risk of SC and control it in the bunker.

This decision tool was tested at the mine for many different scenarios and gave good guidance on how to minimise and prevent SC in the bunker. The SC problem has been reduced to a bare

minimum or closer to a no-event scenario. This was achieved by ensuring that the situation is quickly analysed using the decision tool and proactive measures are put in place to manage the situation.

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# CHAPTER 5
# CONCLUSIONS

In order to achieve what was set out in the problem statement, a few objectives were set. The next few paragraphs will explain these and how they have been realised.

The *first objective* was to review the different areas where spontaneous combustion (SC) is prevalent in coal mines. An extensive literature review was conducted and the findings are presented in Chapter 2. This chapter covered the international and national arena pertaining to this subject. It was found that in South Africa the SC problem is more prevalent in surface mines. Internationally, research indicated that SC is prevalent at both underground and surface mines.

The *second objective* was to evaluate what causes SC in coal stockpiles, dumps and bunkers or silos. Research indicated that the chemical constituents of coal, together with the mining practices and the factors affecting the physical conditions of the bunker, play a role in whether or not SC occurs. The research work provided the latest innovative solutions available internationally which could assist in the prevention of SC and the control of SC fires. This objective was further addressed in the results chapter, Chapter 3, and the analysis and evaluation chapter, Chapter 4.

The *third objective* was to evaluate what preventative measures are available to prevent SC. It was found that the following were the most common techniques for treating SC:

- Understand the coal type and how liable it is to combust spontaneously.
- Understand the mine design and improve it if necessary.
- Improve the mine's management controls and mining practices.
- Increase awareness of the causes of SC.
- Increase the use of risk identification and management strategies.

The *fourth objective* was to understand the affected operational envelope or limits. The findings presented in Chapter 3 have adequately addressed this objective by establishing where the problem actually starts in the mine and where it ends at the bunker outlet point.

Finally, the ***fifth and last objective*** was to establish a systematic process for identifying and preventing SC in raw coal storage bunkers. A decision analyser was created and documented in Chapter 4. The purpose of the decision analyser is to provide a systematic way of addressing SC from the mine to the storage bunker.

This chapter links the outcomes of the study to the agreed objectives. It is evident that the objectives set out at the beginning of the study have been achieved.

# CHAPTER 6
# RECOMMENDATIONS

## 6.1    THE BUNKER DESIGN

- The bunker must be so designed as to prevent dead spots or areas where hotspots can form, as per Figure 6.1a. A proper particle flow analysis can be done by using simple software or a discrete element method to simulate how the material will flow in the bunker or silo, as indicated in Figure 6.1b. The simulation will provide insight into the mass flow/final flow, residence time/product degradation, rat-holing, bridging, blockage, dust formation, bunker/silo shape, cone shape, output dimension and wall thickness calculations.

- The designer must consider the static and dynamic design of the mine. During a normal production process, breakdowns, planned maintenance and scheduled routine inspections occur. At times, this could last for hours and during this period the coal is inside the bunker and most likely to combust spontaneously. It is best to monitor the temperature of the coal continuously during any such abnormal periods. If the coal temperature starts to increase >50 °C, it is best to remove the coal from the bunker. If the coal remains below this temperature, the standing time can be increased because the heat is most likely being dissipated and therefore the temperature of the coal is not increasing. Humphreys (2004) indicated that after 48.9 hours the temperature of the coal could increase exponentially based on the R70 test. The International Maritime Organization(IMO) has a ruling that coal with a temperature >45 °C should not be loaded onto a ship. If a coal cargo temperature on a ship reaches >55 °C, the ship should sail to the nearest port for assistance. Therefore one can assume that a safe duration for the coal standing in the bunker is dependent on the temperature of the coal.

- As in Australian SC management, it would be useful to establish a 'gas evolution laboratory' at the University of Pretoria.

- Install continuous real-time CO monitoring equipment at critical locations of the bunker to discern the intensity of SC.

- Install tanks filled with nitrogen that automatically discharge into the bunker once SC is detected.

- Thermal cameras or temperature probes should be installed to monitor the coal entering the crusher and bunker or silo. This will inform the operator if hot coal is being fed from the mine or source. The installation cost of such a system is <R300 000. However, if the bunker does have an SC incident and depending on the severity of this incident, the revenue impact to the operation could be about R2,923 billion as was shown in Chapter 1, Section 1.2.

- Airflow measurements must be taken in order to establish whether air is entering the bunker or silo. This will influence the oxidation rate of the coal. These measurements must be taken regularly by the mine hygiene specialist using a well-calibrated velocity meter. The method used in Chapter 3, Section 3.6.2, is adequate for this purpose.

- In large bunkers with great heights, the material loading should be controlled to prevent a greater generation of fines than necessary, in order to prevent negative production impacts downstream. This can be achieved by ensuring that the coal in the bunker does not drop to a level less than 50–60% of the height of the bunker. The greater the drop, the greater the fines ratio.

- If the bunker has a number of coal-extraction points, it becomes important to ensure that the sequence of loading coal into the bunker is designed in such a way as to minimise the quantity of air being drawn into the bunker. This will help to prevent oxidation and can be done by ensuring that there is coal at all the extraction points at all times. The process engineer needs to build in a standard operating procedure which will ensure that coal is not drawn off completely from the extraction point. This operating procedure can be applied by using simple instrumentation and programmable software, which will then trigger a warning light to inform the operator when the extraction point is reaching a dangerously low level.

- Depending on the dust being created when the bunker or silo is being loaded, it will be advisable to install explosion-proof equipment in that area or within that control zone. This dust is carbonaceous dust and, if present in an area, it is referred to as a Class II location. The ignition temperature, the electrical conductivity and the thermal blanketing effect of the dust are all critical when dealing with heat-producing equipment such as lighting fixtures and motors. All of these types of equipment are present on a bunker, and must therefore be protected.
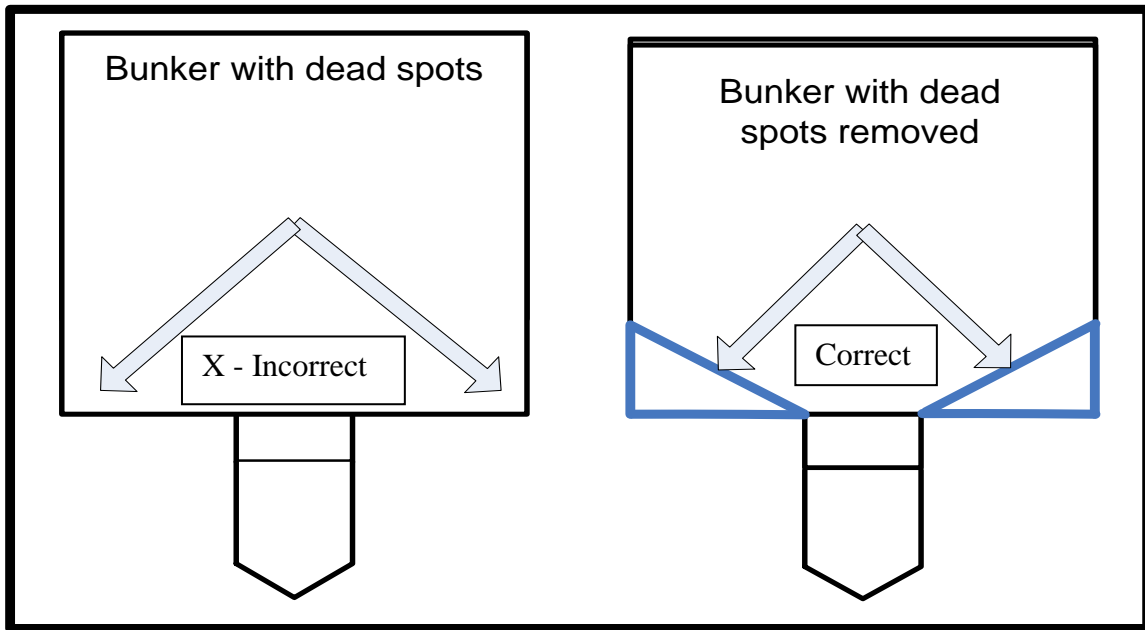
**Figure 6.1a: Bunker with and without dead spots**
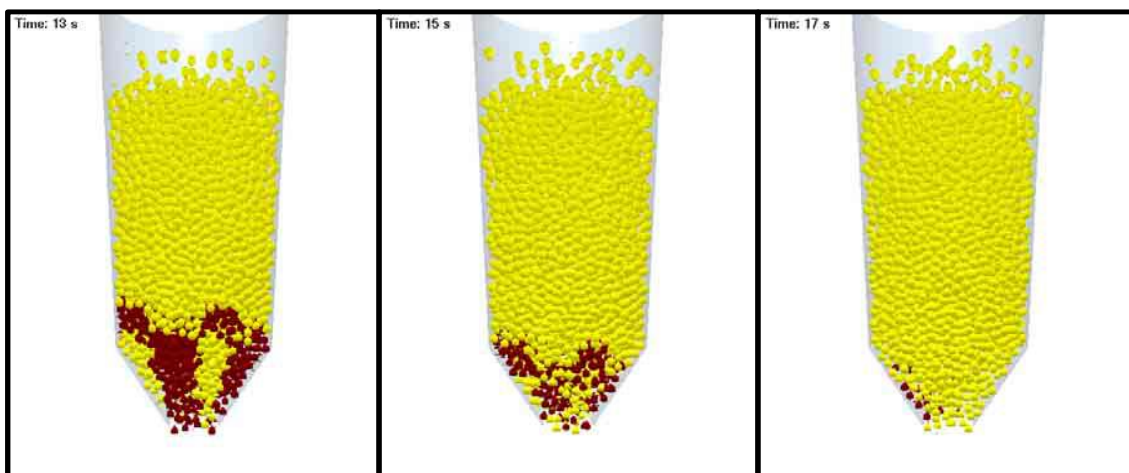


**Figure 6.1b: Flow through a silo**

## 6.2    MANAGEMENT AND CONTROL

- To address the issue of the standing time of coal on the benches, a risk assessment must be done on the mine. Following the risk assessment, a standard operating procedure must be established on how to manage the raw coal standing on the benches. Proper training in this procedure must be provided to all mine personnel.

- Proper mining best practices must be established at the mine to control and treat hot coals. If hot coal is detected, it should be moved to a safe location and allowed to burn out under a controlled environment. After it has been burnt out, it should be disposed of safely. A proper evaluation must be done on what caused the SC and proactive measures must be put in place to prevent its reoccurrence.

- There should be a standard operating procedure for empting the bunker in a controlled manner in the event of SC. This should follow from a proper risk assessment and adequate training of operating personnel.

## 6.3    REFERENCE

Humphreys, D. 2004. The application of numerical modelling to the assessment of the potential for, and the detection of, spontaneous combustion in underground coal mines. PhD thesis, University of Queensland, Australia.

# CHAPTER 7
# SUGGESTIONS FOR FURTHER WORK

Further research should be conducted on thermographic imaging and reporting of temperatures on a coal mine because from the findings of this investigation it became apparent that there is a need to calibrate the thermographic equipment being used to improve the accuracy of the temperatures being reported.

The standing times of loose cubic metres of coal on the production benches containing sulphur need to be further investigated and documented to establish the correct safe standing times.

If SC occurs in a bunker or silo, it is critical to investigate its impact on the structural integrity of the silo or bunker.

As in Australian SC management, it would be useful to establish a 'gas evolution laboratory' at the University of Pretoria.

# APPENDIX A
# 5X5 RISK MATRIX

## Anglo American Plc Risk Matrix

**Hazard Effect / Consequence**
(Where an event has more than one 'Loss Type', choose the 'Consequence' with the highest rating)

| Loss Type (Additional 'Loss Types' may exist for an event; identify & rate accordingly) | 1 Insignificant | 2 Minor | 3 Moderate | 4 Major | 5 Catastrophic |
|---|---|---|---|---|---|
| **(S/H) Harm to People (Safety / Health)** | First aid case / Exposure to minor health risk | Medical treatment case / Exposure to major health risk | Lost time injury / Reversible impact on health | Single fatality or loss of quality of life / Irreversible impact on health | Multiple fatalities / Impact on health ultimately fatal |
| **(E) Environmental Impact** | Minimal environmental harm—L1 incident | Material environmental harm—L2 incident remediable short term | Serious environmental harm—L2 incident remediable within LOM | Major environmental harm—L2 incident remediable post LOM | Extreme environmental harm—L3 incident irreversible |
| **(B/MD) Business Interruption/ Material Damage & Other Consequential Losses** | No disruption to operation / US$20k to US$100k | Brief disruption to operation / US$100k to US$1.0M | Partial shutdown / US$1.0M to US$10.0M | Partial loss of operation / US$10M to US$75.0M | Substantial or total loss of operation / >US$75.0M |
| **(L&R) Legal & Regulatory** | Low level legal issue | Minor legal issue non compliance and breaches of the law | Serious breach of law investigation/report to authority, prosecution and/or moderate penalty possible | Major breach of the law, considerable prosecution and penalties | Very considerable penalties & prosecutions. Multiple law suits & jail terms |
| **(RSC) Impact on Reputation/ Social / Community** | Slight impact - public awareness may exist but no public concern | Limited impact - local public concern | Considerable impact - regional public concern | National impact - national public concern | International impact - international public attention |

### Risk Rating

| Likelihood | Examples (Consider near-hits as well as actual events) | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| **5 Almost Certain** | The unwanted event has occurred frequently; occurs in order of one or more times per year & is likely to reoccur within 1 year | 11 (M) | 16 (H) | 20 (H) | 23 (Ex) | 25 (Ex) |
| **4 (Likely)** | The unwanted event has occurred infrequently; occurs in order of less than once per year & is likely to reoccur within 5 years | 7 (M) | 12 (M) | 17 (H) | 21 (Ex) | 24 (Ex) |
| **3 (Possible)** | The unwanted event has happened in the business some time, or could happen within 10 years | 4 (L) | 8 (M) | 13 (H) | 18 (H) | 22 (Ex) |
| **2 (Unlikely)** | The unwanted event has happened in the business at some time, or could happen within 20 years | 2 (L) | 5 (L) | 9 (M) | 14 (H) | 19 (H) |
| **1 (Rare)** | The unwanted event has never been known to occur in the business, or it is highly unlikely that it will occur within 20 years | 1 (L) | 3 (L) | 6 (M) | 10 (M) | 15 (H) |

### Guidelines for Risk Matrix

| Risk Level | | Guidelines for Risk Matrix |
|---|---|---|
| (Ex) – Extreme | | Eliminate, avoid, implement specific action plans/procedures to manage & monitor |
| (H) – High | | Proactively manage |
| (M) – Medium | | Actively manage |
| (L) – Low | | Monitor & manage as appropriate |

| Risk Rating | Risk Level |
|---|---|
| 21 to 25 | (Ex) – Extreme |
| 13 to 20 | (H) – High |
| 6 to 12 | (M) – Medium |
| 1 to 5 | (L) – Low |

**APPENDIX B**

**RISK ASSESSMENT TEAM**

| NAME | DESIGNATION |
|------|-------------|
| Willem Hoffman | Manager: Human Resource Development |
| Wentzel Christoffel Stoop | Superintendent: Blasting & Loading; Short-Term Planning |
| Wynand van Straten | Manager: Mining Development |
| Andre Lotriet | Thermographer: Diagnostic Engineering |
| Kwena Marais Pitjeng | Full-time Safety Representative |
| Azwindini Gavhi | Head: Hauling |
| Zanoxolo Sijekula Caesar Nokwe | Manager: Mining |
| William Oldham Le Grange | Head: Secondary Equipment and Construction |
| Derik van Zyl | Safety Officer: Mining |
| Mathys Smith | Chief Surveyor |
| Wiseman Jiyane | Head: Loading |
| Ronald Teffo | Superintendent: Hauling & Secondary Equipment |
| Coen Homan | Superintendent: GG7/8 |
| Ronnie Mvelase | Superintendent: GG-Metallurgical product |
| Joyce Peters | Superintendent: GG-Eskom product |
| Hennie Engelbrecht | Manager: Beneficiation |
| Matheus Magwai | Safety Officer |
| Rabyedi Mabula | Safety Officer |
| Builoe Seleka | Full-time Safety Representative |
| Mark Williams | Assistant Manager Engineering - Waste system |
| Kone Rambuda | Head: In-pit Crusher and Discard Backfill |