Safety in Mines Research Advisory Committee

Project Report

Prevention of spontaneous combustion of backfilled plant waste material

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Research agency:

Project Number: **COL 713**

Date: June 2003

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SYNOPSIS

Since Grootegeluk Coal Mine commenced operation in 1980 all plant discards and inter-burden material have been stacked on discards dumps, a practice that has led to the spontaneous combustion of the waste material on these dumps. From 1980 to 1988 many large-scale and laboratory tests were conducted to determine the factors that contribute to spontaneous combustion, but no successful method of preventing or containing the problem was formulated.

Further research into this problem during 1988 by a new team led to the project 'Safe backfilling of the waste material into the operating pit at Grootegeluk Coal Mine', which was included in the Coaltech 2020 portfolio of projects and also comprised SIMRAC Project COL713. Existing problems and past failures were re-analysed and all contributing factors identified. Reactivity tests of all waste materials and investigations of the contributing factors culminated in the construction of a reactivity model. A mathematical risk model was also constructed to evaluate methods of waste handling, based on the existing database of information as well as on all contributing factors. Newly-identified aspects relating to sealing methods for these compartments were examined, and ultimately backfilling into prebuilt compartments was identified as the best method for waste handling. All materials available for sealing, including power station ash, were tested. Overburden from the mine itself, which is available in bulk and is the cheapest of all the materials tested, was identified as the optimum material for sealing the mine's reactive waste material.

On 20 May 2000, a large-scale test of inter-burden backfilling commenced. During March, April and May 2001, two compartments containing inter-burden material with coal from bench 7B and plant discards, respectively, were constructed. The project was implemented successfully; all compartments are stable, and currently all backfilling is based on the same assumptions as those proven in the large-scale test.

The successful implementation of the method has resulted in savings of approximately R10m per annum.

1 INTRODUCTION

1.1 Spontaneous Combustion Phenomenon

1.1.1 Background to the Problem

Spontaneous combustion of coal in terms of underground fires, combustion of coal product and combustion of waste material represents one of the most significant hazards to the safety of workers and to the pollution of the environment.

Wherever coal mining takes place, crushed coal will be exposed to air, which, under the right circumstances, leads to spontaneous combustion. Inadequate prediction and identification techniques, and detection and monitoring methods as well as prevention practices can enhance the dangers of spontaneous combustion. Late detection means that heating will be more advanced in terms of temperature and area affected. In short, the inadequacy to evaluate, measure and control the state of heating leads to catastrophic problems resulting in disastrous outcomes.

To avoid these dangers it is necessary for research and intensive studies to fully understand the problem, to determine the causes and effects and accordingly to develop methods to prevent or minimise the risk of spontaneous combustion.

1.1.2 Basics of Spontaneous Combustion

The phenomenon of spontaneous combustion is not limited to coal but is known to occur in a number of other materials. No matter what material is involved, the basic principles of spontaneous combustion are the same in all cases. Spontaneous combustion is the process by which heat is generated spontaneously within an oxidising substance under conditions that prevent the dissipation of the heat to the environment. Under these circumstances, the temperature of the reacting material will rise, leading in turn to an increase in the rate of reaction and greater heat generation. The accumulation of heat can lead to ignition of the reactant.

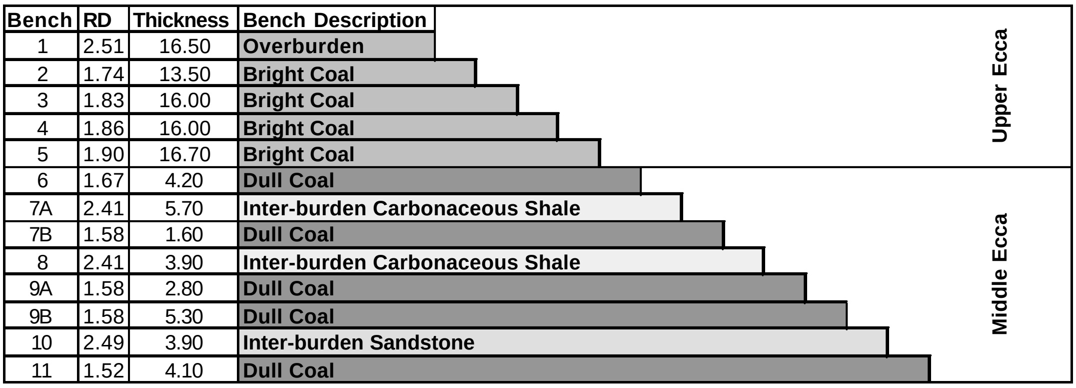
1.2 Grootegeluk Spontaneous Combustion Problem

1.2.1 Background to Mining Operations

Grootegeluk Coal Mine, situated in the Limpopo Province, is the largest coal mine in South Africa (total production 54 Mt per year) and the first (and only) open pit mine in the Waterberg Coalfield, which is the largest coalfield in South Africa. The coalfield is relatively small in area, but is one of the most important coalfields in the Republic of South Africa in terms of *in situ* reserves, containing approximately 50 % of the coal reserves of South Africa. The Waterberg Coalfield spans about 88 km east to west, and some 40 km north to south and continues westwards into Botswana. The coalfield is bounded by faults along its northern and southern limits. The Daarby fault, with a displacement of 250 m, divides the Waterberg Coalfield into two areas: a shallow western area, where the coal can be extracted by surface mining methods; and a deep north-eastern area, where the coal occurs at a depth of at least 250 m below surface.

Grootegeluk Mine is in the shallow area of the Waterberg Coalfield. The coal deposit forms part of the Ecca Group, and 11 coal-bearing zones can be distinguished. The coal seams mined at Grootegeluk Mine form part of the upper and middle Ecca. The upper Ecca is on average 60 m thick, and consists of successions of inter-bedded shale and bright coal. It is a typical multi-seam deposit, consisting of coal beds varying in thickness from a few centimetres to just more than 1 m, closely inter-bedded with mudstone over the total thickness of 60 m. The Middle Ecca, on average 50 m thick, forms the lower part of the deposit and consists of dull coal and carbonaceous shale, as well as grit and sandstone.

Information on the coal bearing strata, as well as geological and analytical data, were obtained from exploration boreholes in the multi-seam, multi-product coal deposit. Using this data, a geological model was constructed according to the geological contacts that apply to the various mine benches. The heights and composition of the benches are illustrated in ***Figure 1.1***.



Bench	RD	Thickness	Bench Description	
1	2.51	16.50	Overburden	Upper Ecca
2	1.74	13.50	Bright Coal	
3	1.83	16.00	Bright Coal	
4	1.86	16.00	Bright Coal	
5	1.90	16.70	Bright Coal	
6	1.67	4.20	Dull Coal	Middle Ecca
7A	2.41	5.70	Inter-burden Carbonaceous Shale	
7B	1.58	1.60	Dull Coal	
8	2.41	3.90	Inter-burden Carbonaceous Shale	
9A	1.58	2.80	Dull Coal	
9B	1.58	5.30	Dull Coal	
10	2.49	3.90	Inter-burden Sandstone	
11	1.52	4.10	Dull Coal	

Figure 1.1: Grootegeluk Coal Mine – Coal Zones/Mining Benches

The mine has the largest coal washing facility in the world. Clean coal production at Grootegeluk is about 16 Mt per year and consists mainly of four products, namely coking coal, power station (steam) coal, metallurgical coal and PCI coal. The vision for 2005 is to reach a production of 17 Mt of product per year. Since the raw coal is of high ash content, large coal beneficiation plants are needed to meet the production targets. For this reason, five plants have been erected since 1980 to produce the quantities of coal shown in ***Table 1.1***.

Plant	Coking Coal	Steam Coal Power station	Metallurgical Coal	PCI Coal	Total
GG1	1.70×10^6	5.101×10^6			6.80×10^6
GG2		5.52×10^6			5.52×10^6
GG3		2.38×10^6			2.38×10^6
GG4/5			0.69×10^6	0.54×10^6	1.23×10^6
Total	1.70×10^6	13.00×10^6	0.69×10^6	0.54×10^6	15.93×10^6

Table 1.1: Final Product produced by Grootegeluk Mine [ton per Annum]

The Grootegeluk 1 Plant (GG1) produces both coking and steam coal, while the Grootegeluk 2 and 3 Plants (GG2 and GG3) produce only steam coal for Matimba Power Station. In the raw coal, layers of sandstone and shale are found in finely inter-bedded layers. Because of this fine shale/sandstone, the first step in the beneficiation process is to crush the raw coal to finer sizes to liberate the coal. Beneficiation takes place in two stages. The first stage is the separation of an intermediary coal product from waste material. This product is then split into a middlings product (power station coal) and coking coal during the secondary washing stage. The separation processes that are used in the different plants are static drum heavy medium separation, cyclone heavy medium separation, spiral classification and hydrosizer classification.

The beneficiation plants that handle the coal from the various mining benches are shown schematically in ***Figure 1.2***.

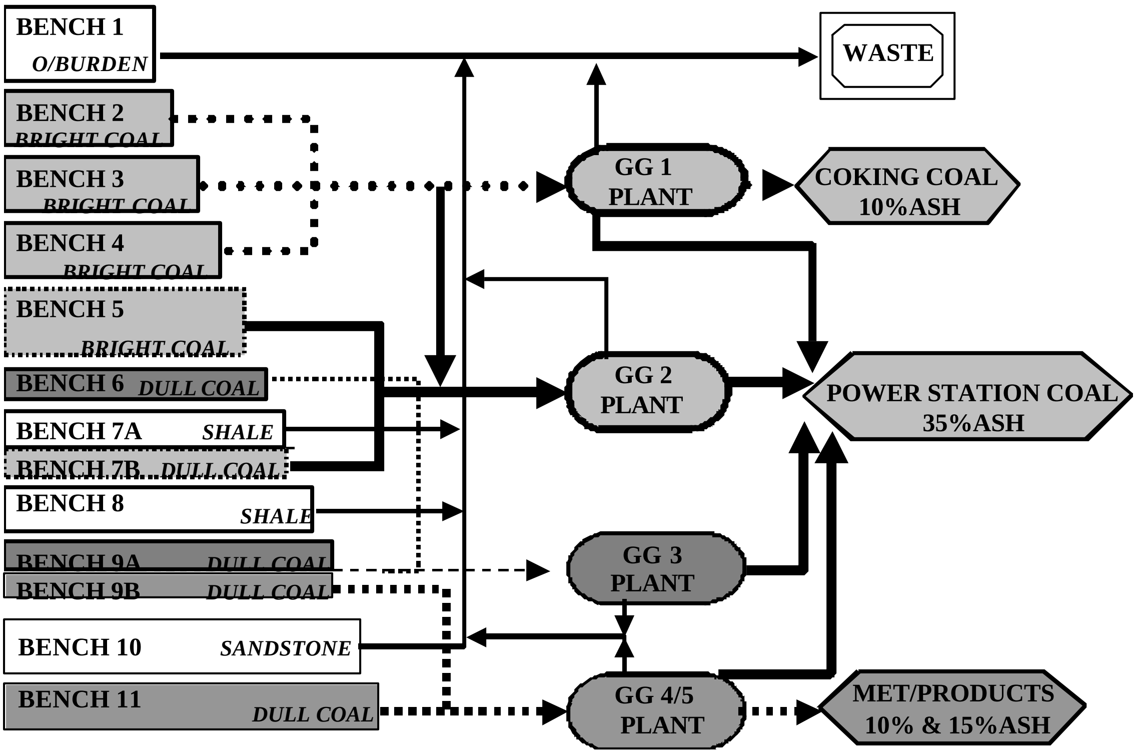


Figure 1.2: Grootegeluk Material Flow Diagram – Coal Beneficiation

1.2.2 Discussion of Spontaneous Combustion Problem at Grootegeluk

At 34 Mt per annum run-of-mine coal production and a yield of about 50 %, the mine produces 17 Mt per annum of plant discards during the beneficiation process. The plant discards have a relatively high propensity towards spontaneous combustion due to their high carbon content (ash content of 75-80 % and a calorific value of 3-7 MJ/kg). The inter-burden material is also very prone to combustion due to its carbonaceous nature. The problem associated with this large quantity of waste is its safe storage and disposal in a way that will prevent the occurrence of fires. The type and quantity of waste produced by Grootegeluk Mine are shown in ***Table 1.2***.

Material	Production [Mt/year]	Volume [Mm^3/year]	RD	Ash [%]	CV [MJ/hg]
Overburden	12.29	6.83	1.8		
Discards	17.32	9.12	1.9	71.88	5.88
Inter-burden (B7A & B8)	5.28	2.93	1.8	77.76	2.53
Inter-burden (B10)	1.72	0.91	1.9		
Total	36.61	19.79	1.85		

Table 1.2: Waste Material produced by Grootegeluk Mine [ton per annum]

The discard materials that need to be handled are mixtures of discards from various plants and waste from benches with unknown properties. The lack of detailed knowledge about material properties complicates the design of a "safe" heap. Thorough knowledge of the chemical and physical properties (***know your coal***) of all the different materials and mixtures was considered to be a prerequisite for the design of safe waste dumps/heaps.

1.2.3 Grootegeluk's Research

Many researchers from universities and research institutes around the world and from Iscor Head Office have investigated the spontaneous combustion phenomenon at Grootegeluk Coal Mine. The most important findings will be discussed.

Since the early 1980s, Grootegeluk's problems with spontaneous combustion were studied and investigated by Professor D. Glasser of the University of the Witwatersrand. This research was critically important to Grootegeluk as it resulted in a number of recommendations regarding preventative methods as well as advice on mining activities to minimise the risk of spontaneous combustion.

1.2.4 Grootegeluk's Large-scale Tests Experience

Initially, Grootegeluk produced coking coal only, and the middlings produced needed to be stored before the nearby power station was built. Grootegeluk Mine management foresaw that the disposal of middlings and the plant discards would give rise to a spontaneous combustion problem and, therefore, in the early 1980s they established a research team at Iscor, which, together with universities around the world, investigated the best disposal and storage methods for these materials. For the storage of middlings a successful method was identified.

Successful storage of middlings for more than 11 years before being reclaimed
An 11^0 angle for the final side slopes of the stockpiles was proposed and the height was limited to an average of about 18 m to reduce the effect of wind pressure differentials. It was proposed to stockpile in 0.5 m compacted coal layers (see ***Figure 1.3***). The stockpiles were equipped with thermocouples and gas sampling probes in order to monitor the temperature and gas emissions continuously.
The specifications for the middlings were as follow: ash 35 %, sulphur 1.4 %, CV higher than 20,0 MJ/kg, and volatile about 22.0 %.

Figure 1.3: Storage of Middlings

The following results and observations were obtained from the measurements taken. Oxygen concentration was observed at the surface of the dump only, with negligible oxygen quantities being found deeper than 1 m from the surface and no oxygen being found at a depth of 2 m. Oxygen penetration into the dump increased with time (about 0.3 m in five years) as a result of the age function. The temperature inside the bed varied between 30 ^{0}C and 35 ^{0}C.
These conclusions are limited, only proving existing knowledge regarding spontaneous combustion. The risk of spontaneous combustion was minimised by compaction, angle of slope, height of dump, and reduction of particles size (very reactive, small particles on the surface of the dump). However, the risk of spontaneous combustion could increase in time, due to the increasing depth of oxygen penetration over time.
This method is not applicable to Grootegeluk's waste material due to the large volume and particle size distribution of the waste. Crushing and segregation of waste increases the running costs of waste handling and, together with required capital, makes such a method not economical for this scale of operation.
In order to determine the best method of waste handling, the Grootegeluk Mine management decided in the early 1980s to control and monitor the first disposed waste material. While these tests did not provide a solution to Grootegeluk's problem, they did contribute crucial information for the current research. All large-scale tests and experience regarding the behaviour of Grootegeluk's waste material is discussed below.

Stacking of discards in 1980, about 12 m high without compaction, crushing or other preventative methods

The plant discard dumps were monitored by means of thermocouples, gas sampling and an infrared thermograph for about five years. The first dump was planned in two sub-levels, each level with a height of 12 m.

The following situation arose. The dumps remained safe for more than three years, after which period problems arose when the second sub-level was developed (see ***Figure 1.4***). A stacker was used to construct the dump and the –150 mm plant discards resulted in segregation. The high permeability at the toe of the dump allowed easy access for oxygen into the dump and combustion started, within a few months, when the second sub-level covered the first sub-level.

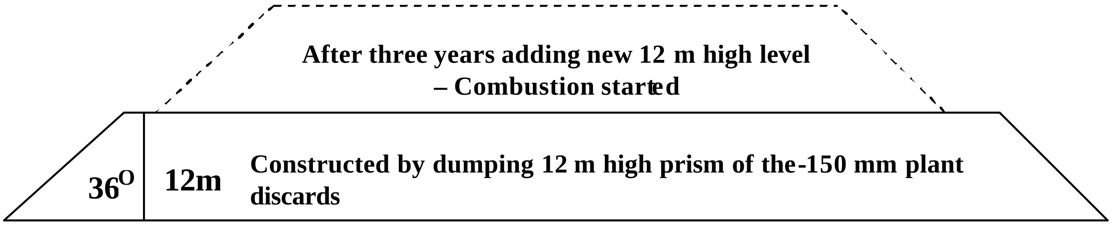


Figure 1.4: Stacking of discards in 1980

From the analysis of the findings it can be concluded that the risk of spontaneous combustion can be increased by reducing dissipation of generated heat.

Increasing the height of the dump, and allowing segregation and therefore oxygen to penetrate into the dump, increases the risk of spontaneous combustion.

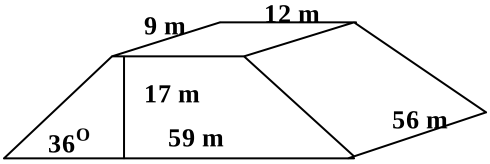
Adding new material (possibly more reactive) onto a dump that is already at risk activates spontaneous combustion.

Crushed waste test heaps in 1985

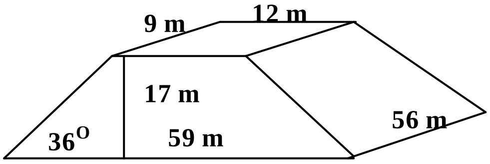
To establish the influence of the particle size of waste material on the propensity for spontaneous combustion, the project team constructed five different dumps containing different sizes of waste material. Plant coal waste was crushed and segregated. The material was stacked into a cone from a height of 17 m. The cone was then extended to contain about 50 000 t of material with a top plateau of about 9 m x 12 m. There was significant segregation during stacking. During construction an array of 20 thermocouples and gas sample pipes was installed within each heap. Five heaps were built and instrumented with the respective top sizes of the waste material being –6 mm, -10 mm, -15 mm, -25 mm and –180 mm (as produced by the plant, without segregation) (see ***Figure 1.5***).

The following results were obtained. All heaps burnt within two years of the start of the test. A temperature of 70 °C was reached within 4.5 months by the –6 mm, -10 mm, -15 mm and –25 mm heaps. The –180 mm heap reached 70 °C after 14 months. The maximum temperature in the –180 mm heap was recorded after 16 months and was higher than 1 000 °C. The position of the heat epicentre was located halfway between the slope's toe and the top of the heap. The maximum temperature in the –25 mm heap was recorded after eight months and was less than 900 °C, which indicated that the epicentre was closer to the slope, one-third of the distance between the toe and the top of the heap when measuring from the toe. The maximum temperature in the –6 mm heap was recorded after seven months and was less than 500 °C. This indicated that the epicentre at the slope was close to the toe.

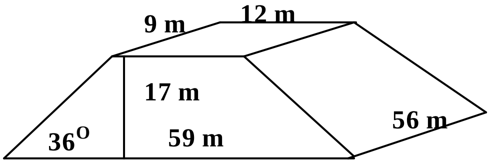
The conclusions from this test are as follows. The oxygen supply rate and the oxidation rate are dependent on the permeability of the waste material (smaller size, higher oxidation rate but lower supply rate). The maximum temperature is dependent on the availability of oxygen, and therefore on the permeability of material (larger particle size means more oxygen available and a higher temperature). The time at which the critical temperature is reached is dependent on the heat dissipation and reaction rate. For low permeable material (small particle size), the reaction rate is very high at a very low head dissipation rate, due to the low rate of gas movement. Heat dissipation decreases with a decrease in particle size.



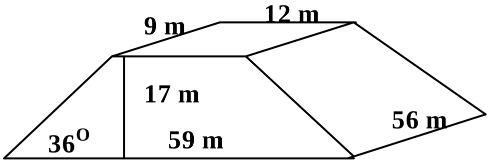
50 000 t –6 mm Plant Discards



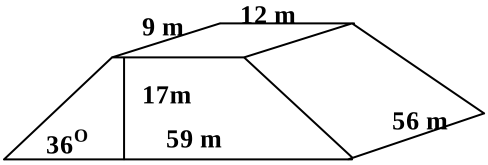
50 000 t –10 mm Plant Discards



50 000 t –15 mm Plant Discards



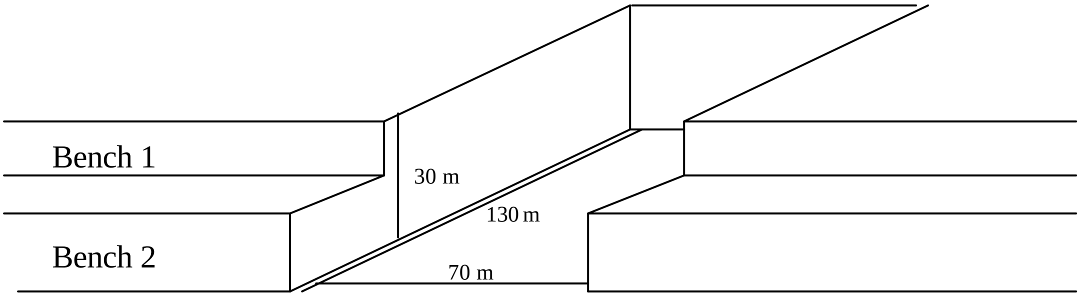
50 000 t –25 mm Plant Discards



50 000 t –180 mm Plant Discards

Figure 1.5: Crushed waste test heaps in 1985

Large-scale test performed in 1988 in a prepared excavation within the pit of Grootegeluk
Considering backfilling of waste material, the project team, together with the Grootegeluk Mine management, decided to prepare a large-scale test within the Grootegeluk pit. The test site was a box-cut excavated into the top two benches surrounding the open pit. The excavation was about 70 m wide by 130 m long by 30 m high (see ***Figure 1.6***).



Prepared Excavation

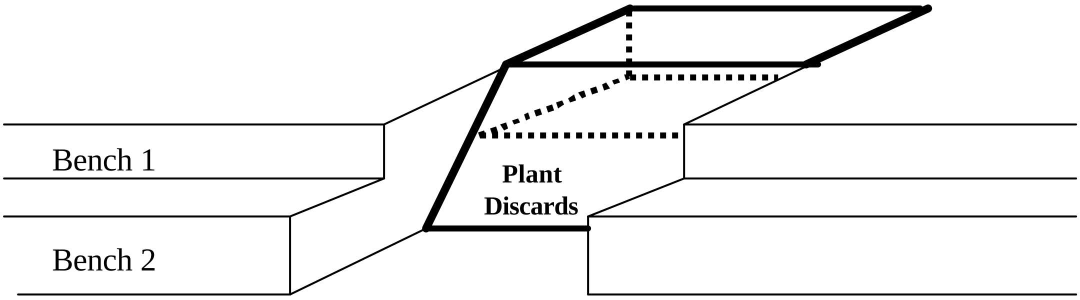


Figure 1.6: Test performed in 1988 in a prepared excavation within the pit of Grootegeluk

A simulation of stacking inside of the pit was prepared for this test. Thermocouples and gas sampling instruments were installed to measure the temperature and gas emission. The project team expected that the material, which was shielded from three sides, would be sufficiently guarded against wind penetration into the dump and from the ingress of large quantities of oxygen into the dump. The following results were obtained: ignition required 12 months; and newly added discard material caught fire within weeks.

Conclusions from this test are trivial. One open site for oxidation is enough to ignite a fire, while protecting three dimensions of a dump does not prevent oxygen transportation into the dumps. Shielding decreases heat dissipation, and shipping proves this conclusion. The higher the initial temperature, the higher the rate of oxygen absorption and the quicker combustion occurs.

Radial Stacking Method

Currently all waste material from Grootegeluk's plants is stockpiled according to the radial stacking method with 40 m downward stacking and 18-20 m back stacking (see ***Figure 1.7***). The slopes and the surface are covered by red sand available on site. However, the use of sand for sealing purposes was evaluated as "not successful" by Eichenberg in 1984 and Brooks in 1980. The very low stacking rates, especially at the centre of the stacking, allow spontaneous combustion within the stacking area. The red sand does not preventing spontaneous combustion but reduces the consequences of spontaneous combustion, allowing people to work within this area.

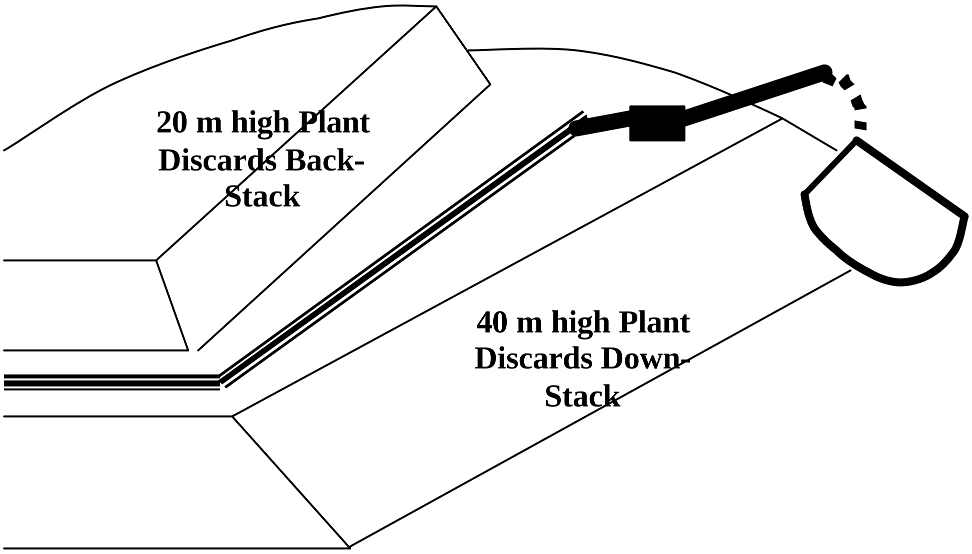


Figure 1.7: Radial Stacking Method

The following observations were noted: the angle of the slopes is the natural angle of pile with full segregation of particles; and the slopes are exposed to air for a long period of time before they are covered by red sand and later by the new, freshly stacked material. It was observed that the waste material in back-stacking starts to burn within a few weeks after stacking, especially at the centre of the stacking radius, and that the waste material starts to burn within a few weeks after covering with a layer of red-and.

Conclusions from experience with the existing stacking method prove that the geometry of the dump leads to a low stacking rate, allowing spontaneous combustion to occur. The initial height of the dump is too large, allowing full segregation to occur at the natural angle of the slope. Furthermore, the natural angle of the slopes allows the wind to have a big influence on the oxygen transportation into the dumps and also the very good segregation of particles at the slopes produces "a chimney effect". The red sand is a very inefficient material for isolating the oxygen diffusion. It causes thermal isolation for heat release but does not isolate the oxygen. It is extremely dangerous to cover the dump after a delay, since low-temperature oxidation (cold oxidation) is advanced.

1.2.5 Conclusions from Grootegeluk's Experience

These early experiments and experience as well as research form the basis from which the current research proceeded. The general conclusions allowed for the formulation of strategies to minimise the risk of spontaneous combustion:

- Use sealing to reduce oxygen inflow.
- Speed up stacking rates to ensure stack faces are exposed for a minimum period (this will need careful planning and will probably be used in conjunction with other techniques).
- Compact the top layer of stacked material.
- Avoid uncontrolled segregation during stacking through modification of size distribution and stacking methods.
- Minimise the probability of deep-seated combustion.

1.3 Need to use Backfilling Techniques

1.3.1 General Discussion

Due to the negative environmental impact of Grootegeluk's dumps and the rising costs of waste handling, it is essential to investigate the spontaneous combustion of low reactive waste material, in order to design a safe method of backfilling. Air pollution, water pollution and damage to the surrounding area due to continual growth of the area affected by dumps are seen as negative impacts on the environment. The rising cost of waste handling is due to a continued increase in hauling distance for inter-burden and overburden, an increase in the height of the dumps as well as the continued increase in the price of diesel.

1.3.2 Backfilling Objective for Grootegeluk Coal Mine

The goal is to decide on the backfilling method most suitable in the following aspects:

- **Minimal Risk** of spontaneous combustion, local ignitions, and late ignitions
- **Safety for the longest possible period** in terms of minimal influence of pollution on the pit's workers and environment
- **Minimal Cost** for meeting the objective with regard to a method and environmental impact of the method
- **Maximum Safety** conditions acceptable to all workers in the pit, within the requirements of the law
- **Uncomplicated Technology and Simple Code of Practice** for meeting objectives in light of technology, system availability and reliability, and skills of present labour force

1.3.3 Backfilling Requirement for Grootegeluk Coal Mine

The backfilling method must fit in with the mine design specified in the long-term planning of Grootegeluk Coal Mine with regard to rehabilitation, optimal exploitation and utilisation of minerals and ISO14000.

2 MODELLING OF CONTRIBUTORY FACTORS AND THEORY OF RISK ASSESSMENT

2.1 Contributory Model

The database containing the research and practical experience gained from previous scientists on the spontaneous combustion problem at Grootegeluk Mine enabled the author to analyse all the relevant contributing factors. From this data, a contributory model was designed (see ***Figure 2.1***), which played a cardinal role in solving the spontaneous combustion problem at this mine.

It was deemed necessary to classify all the factors contributing to heat generation and heat dissipation. The contributory model reflects the severity of individual parameters that contribute towards the overall risk. This feature helps to identify major factors in self heating and will be useful in the design of a risk assessment model. Through the use of this model, the priorities of the different risks can also be determined. This contributory model considers not only the material properties, but also the mining and environmental conditions, and is discussed in more detail in the following sections.

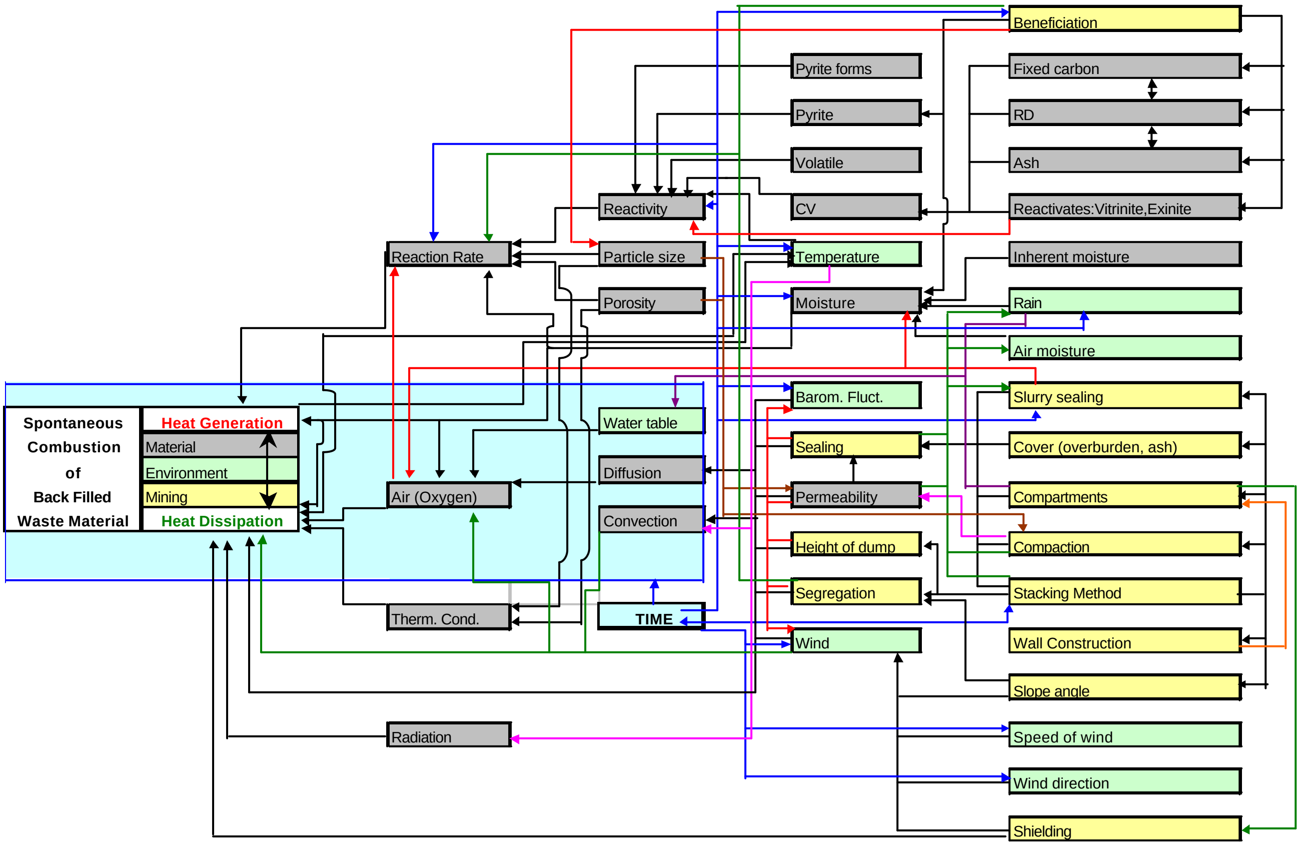


Figure 2.1: Grootegeluk's Backfilling Contributory Model

2.2 Required Input Data for Contributory Model

The initial database did not contain all of the information required to build a useful contributory model. The lack of detailed knowledge about material properties complicates or even makes impossible the design of a backfilling risk assessment method and is most certainly insufficient for the purpose of making accurate decisions or assumptions. It was necessary to advance the current state of information regarding reactivity of waste material as a basis on which precise decisions and assumptions could be made. In this thesis, information on material properties will be used as an important input into the mathematical model that will be developed, i.e. the contributory model, to determine the overall risk of material that is stored under certain conditions.

2.3 Chemical and Physical Properties required for Model

Classification of coals requires some methodology for measuring their chemical, physical and industrial properties. For this purpose, a variety of standard analytical procedures are available world-wide from reputable standards organizations. Some of the more familiar ones include the International Organization for Standardization (ISO), the American Society for Testing and Materials (ASTM), the British Standards Institution (BS), the Standards Association of Australia (AS), and the Association Francaise de Normalisation (AFNOR). Because these organizations may support different standards for the same test, the standard practice used should always be identified, but more importantly the procedures described in these standards should be followed in every detail. For the purposes of this investigation, those methods specified by ISO were used to determine the chemical and physical properties of the different materials from Grootegeluk. In addition to these standard methods to determine basic properties (proximate analysis, ultimate analysis and a petrography investigation), specific tests were developed to determine the coal's reactivity towards oxygen. These tests expressed reactivity as cm^3 oxygen absorbed by a kilogram of coal per day. The tests that were used for this purpose are the Glasser Test (small-scale test using 50 g pulverized coal) and the Strauss Test (using 5 kg coal with particle size range of < 6.1 mm), which are described later. For verification purposes the samples were also submitted for the WITS-EHAC test. All three tests are described later.

The routine moisture, ash, volatile, sulphur-pyrite and CV tests were performed on all the samples representing discards from all plants resulting from the processing of material from each bench as well as inter-burden material. An additional petrography study of such samples was also undertaken. On the basis of the results of reactivity testing, fluctuations in reactivity and correlated factors of plant discards were identified. The new database allowed the building of a database mathematical risk model (DMRM). The DMRM permits the identification of critical considerations for Grootegeluk's backfilling.

Analysing fluctuation in the risk of spontaneous combustion as a function of time, using the DMRM, and investigating the probability of the maximal and minimal risk, one of the key factors in backfilling design, the critical time for material exposure, was established. This information was used to determine the backfilling dimensions of stacking levels and compartments and therefore also enabled determination of a safe stacking rate regarding the exposure of the material.

By making the assumption that backfilling in pre-built compartments is potentially a solution for the Grootegeluk spontaneous combustion problem, the research turned further to the sealing method for compartments. The research also focused on the optimal material for sealing that is available at Grootegeluk and the sealing model.

To select the best sealing materials, a series of laboratory tests were undertaken. These tests allowed the selection of the best material for sealing purposes, that is available in huge volume and which creates the most economical sealing solution.

Compaction, the recognised preventative method, is not applicable at Grootegeluk due to the huge volume and size distribution of waste material required and can be only considered for the surface area of the dumps.

2.4 Procedure for Development of Risk Assessment Model

A risk assessment model (DMRM) was constructed using the contributory model and results available from the discussed tests. The DMRM is based on the risk assessment model introduced by Bystron & Urbanski. This model is discussed at a later stage.

3 LABORATORY TESTING OF THE REACTIVITY OF WASTE MATERIAL FROM GROOTEGELUK, INCLUDING THE SEALING PROPERTIES OF INERT MATERIAL

The problem, as defined in Chapter 1, is to store reactive waste material within an enclosure made from inert material so as to prevent spontaneous combustion from creating a problem within the working open pit. A series of laboratory tests were undertaken to characterise the available reactive and inert materials.

Experimental facilities were established at the University of the Witwatersrand and at the laboratories at ISCOR Head Office at Monument in Pretoria.

3.1 Test Facilities

Small-scale tests to determine fundamental indices of reactivity were developed by the University of Witwatersrand and made use of both oxygen depletion rates and the well known crossing-point temperature method. A longer term test to determine the progress of oxygen absorption was developed by ISCOR and a pilot scale simulation of the envisaged application on the mine was also undertaken using a column test at the ISCOR laboratory.

3.1.1 Reactivity Tests

Three different reactivity tests were undertaken to obtain the data necessary for the reactivity model.

WITS-EHAC liability index
The differential thermal analyser used for these tests was developed and built at the Department of Mining Engineering, University of the Witwatersrand, and was initially designed for coal from the Witbank Coalfield. The analysis method is based on the principle of differential thermal analysis and involves a 20 g sample. The apparatus consists of six brass chambers immersed in a temperature-controlled oil bath. Airflow through each chamber can be controlled and the temperature of each sample is monitored by a platinum resistance thermocouple. Four of the six chambers are usually filled with coal samples (each approximately 20 g) and the other two are filled with 20 g of an inert substance. The samples are heated and the temperature difference between the coal and the inert reference material is measured and plotted against the temperature of the inert material to obtain a thermogram. The WITS-EHAC Spontaneous Combustion Liability Index is calculated from the results and materials are classified as a Low (<3), Medium (3-5) or High (>5) Risk.

Glasser small-scale oxygen absorption test
This is a very uncomplicated and inexpensive test that uses a 100 cm^3 glass conical flask with a female ground glass joint on the top, and a U-tube. The U-tube is fitted with a male ground glass joint on the one end and a burette with two graduated sections on the other end. The upper graduated section can measure 10 cm^3 with an accuracy of 0.1 cm^3, while the lower section can measure 3 cm^3 with an accuracy of 0.05 cm^3. This end is inserted into a 100 cm^3 squat form glass beaker containing liquid paraffin. The conical flask allows a sample of size of 10 g to 50 g to be used. The apparatus is designed to measure the volume of oxygen absorbed by a given mass of coal per unit of time, by means of a graduated burette. The reactivity is expressed as ml of oxygen consumed per kg per day.

Strauss large-scale oxygen absorption test
The apparatus consists of a 10 litre, high density PVC reaction vessel. A 5 kg coal sample with a particle size of between 1 and 6.5 mm is used to determine the oxygen reactivity. At intervals of a few hours, gas samples are removed from the vessel through a rubber septum and the rate of oxygen depletion (first order reaction rate constant “k”) is determined by gas chromatographic analysis. The oxygen reactivity is calculated and expressed as cm^3 of oxygen consumed per kg of coal per day.

3.1.2 Reactivity Test with Sealing

As an extension of the small-scale reactivity testing, Professor D. Glasser suggested, during a spontaneous combustion meeting at Iscor Head Office in 1998, that a column of reactive material be used to obtain a more realistic assessment of oxygen depletion, particularly as a function of depth and reactivity of such material.
It was felt that with highly reactive material, oxygen depletion could occur at shallow depth and therefore that heat dissipation would be complete and temperature increase would not occur, i.e. spontaneous combustion would be avoided. In very low reactive material, the very slow rate of heat generation, even deep in the pile of material, would also prevent spontaneous combustion.

The column test was developed to determine to what extent the depth of penetration of oxygen, drawn from the surface of the column, into reactive material is dependent on the reactivity of such material. In addition, the column test measures the reactivity of large samples of waste material, without the need to crush or screen the material, by observing the curve of oxygen depletion. To analyse the oxygen concentration profile, a simple apparatus, comprising a 3 m high, 20 cm ID plastic column filled with coal, was designed by Professor D. Glasser.

Iscor adopted this proposal of Professor D. Glasser and, to test this reasoning, a 150 mm diameter, metal column, 3 m high, was built and used for two tests in early 1998. The first test using this apparatus mainly confirmed the results of the Glasser small-scale test, while the second test, involving more reactive, moist material, resulted in a slow, steady temperature increase. However, because of the thermal conductivity of the walls of the column, test results could not be considered representative of the practical situation. From these two tests sufficient interest in column testing was generated and four 3 m high, 350 mm PVC columns were constructed. Each column was closed at the bottom and open to the atmosphere at the top only. Each PVC column consisted of six 0.5 m high sections, and could be filled with the test material, (see ***Figure 3.1***). The top sections were normally filled with a certain thickness of sealing material, while the bottom was filled with coal or coal waste. Four columns were constructed in order to study a large number of variables with a reactive line, with the tests including a variation in sealing thickness with a constant type of sealant and a constant amount and type of coal. The tests can alternatively include different types of sealing material with a constant thickness. To ensure uniform results, the same type of coal was used to test the sealing materials. The efficiency of the sealing material was measured by observing the depletion of oxygen within the reactive material. After loading, the sections were assembled and the joints sealed with silica sealant and clamped to obtain a 3.0 m high column. Each section was fitted with handles on the side and an iron-mesh at the bottom, allowing the manual stacking of the fully loaded, individual column sections. Immediately after assembly, the material contained inside the column was flushed with nitrogen through a valve installed at the bottom of each column. Oxygen was then allowed to enter by diffusion from the top of each column.

The columns were used for three series of tests:

a) To determine the best sealing material.
In these tests the reactive material was kept constant (10 % ash coking coal product), the thickness of the sealing material was kept constant (2 m) and all the potential sealing materials available at the mine were tested in sequence.

b) To determine the effect of sealing material thickness.
In these tests the reactive material was kept constant, as above, the sealing material was kept constant (the most promising of the materials used in a) was chosen) and the thickness of the sealing material was varied (0.5 m, 1.0 m, 1.5 m and 2.0 m).

c) To determine the influence of the same sealing on materials of different reactivity.
In these tests a 2 m thick layer of the best sealing material (weathered overburden) was used above a variety of reactive materials (10 % coking coal, as above, plant discards, Bench 7A inter-burden and Bench 8 inter-burden).

Gas samples were tested after one day, three days and seven days. Thereafter sampling was conducted at intervals of seven or 14 days until completion of the test, lasting usually for a few months. The longest running test was eight months in duration.

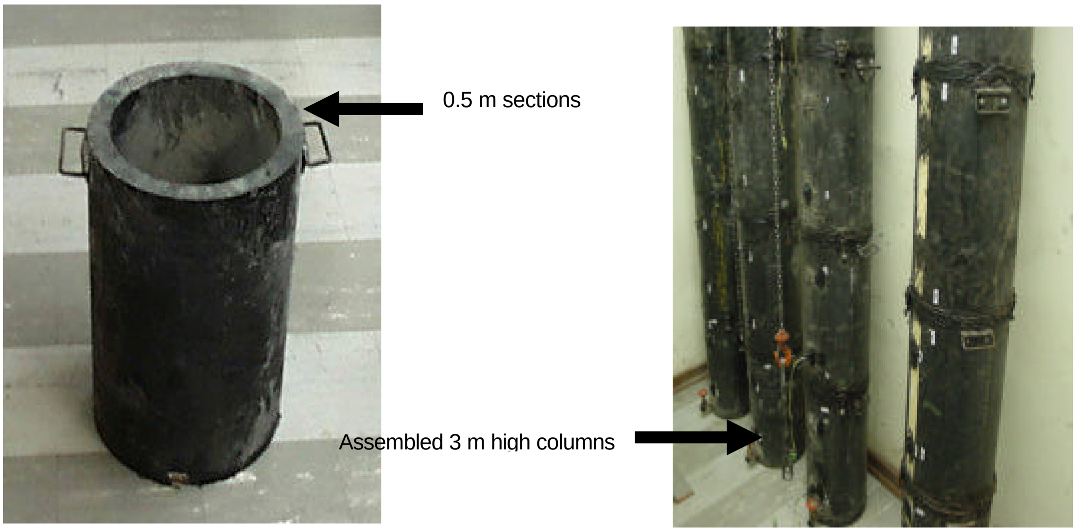


Figure 3.1: Column Test Apparatus

3.2 Test Samples

For two of the three series of column tests, it was important to keep the reactive material constant. The 10 % ash coking coal was obtained from the sampling chute on the conveyor product belt of the GG1 Plant. The ash content of material on this belt was determined using a permanently mounted monitor, which was checked before sampling took place. The same method was used to obtain a 15 % ash product.

For the test using different reactive materials, it was extremely difficult to obtain good representative samples of plant discards, originating from each of the 10 benches and processed by the four plants, GG1 to GG4/5. The representative sample for the column test was obtained while all GG plans were running.

To overcome this problem to obtain a representative sample for the reactivity tests, drill core material from the 10 benches was obtained and processed through a pilot-scale plant. The pilot plant simulated the operation of the four plants and it is reasonable to assume that the full range of discard being generated by GG was obtained and used in the reactivity tests.

During the first quarter of 1999, a hole was drilled through all the benches. The hole had a depth of 110 m. The drill core material then received similar treatment to normal plant samples (but on a pilot-plant scale) to simulate representative discards from all plants for each bench. Sampling material from benches 2 to 4 were treated to represent discards of the coking coal and the middlings by changing the cut RD from 1.85 to 1.95. Material sampled from benches 9B and 11 were treated to represent discards of the metallurgical products (10 and 15 % ash) by changing the cut RD from 1.46 to 1.64 in the case of bench 9B material, and from 1.41 to 1.54 in the case of bench 11 material. Material from the inter-burden benches was sampled without beneficiation. Directly after sampling, the materials were sealed in nitrogen to prevent oxidation.

Some of these materials were submitted by Iscor's Geology Department for standard laboratory tests during which the physical and chemical properties as well as the petrography were determined. The remaining materials were used for all reactivity tests.

Seven different sealing materials were selected for use, with the criteria that they were readily available in bulk on the mine and that cost should be considered. The materials were Grootegeluk weathered overburden material, wet Grootegeluk overburden material, Grootegeluk red sand, dry Matimba Power Station ash, wet Matimba Power Station ash and Grootegeluk dry and wet slurry. All of these materials, except for the weathered overburden, were relatively uniform in nature and representative samples were easy to obtain. With regard to the weathered overburden, the Grootegeluk pit is approximately 2.5 km wide and the overburden varies from sandy in the south to clay in the north. To obtain a representative sample, 12 drums (100 kg each) of material were obtained from different places in the overburden, i.e. one drum taken from each loading block along the overburden strip. This material was taken to the laboratory and mixed together in preparation for the column tests.

3.3 Test Results

The problem, as defined in Chapter 2, is to build a useful contributory model to provide important input into the development of the mathematical risk assessment model. The measured material properties and the full range of mining and environmental conditions were necessary to develop such a risk assessment model.

3.3.1 Reactivity Tests

The most important parameter is the reactivity of the waste material representing each individual bench and this is dependent on the beneficiation required to obtain different products. Other important data on the chemical and physical properties, as well as the petrography of the waste material representing each bench, was obtained from standard tests carried out by the Geology Department of ISCOR. This data is presented in ***Tables 3.1 and 3.2***.

The data, representing each possible waste type, was used for further modelling of the plant discard mixtures. These mixtures depend on which plant is running and its capacity. The possible combinations were evaluated, over a one-year period, by studying the actual data from the plants.

Using data obtained from the Strauss and Glasser tests, the relationship between reactivity and age of the sample was found. This function was crucial to determining the reactivity loss over time of coal waste materials.

Properties of waste material representing each bench's waste

Material from each bench is either crushed, screened and sold as raw products, or sent to a single plant or to several plants, depending on its phosphor and sulphur content and on the product yield, e.g. coking, steam or metallurgical coal. It is however important to understand the reactivity of the waste material that comes from each bench. In some cases, the material from a single bench needs to be examined several times depending on how it is mined, the plant to which it is sent and the product split. In ***Figure 3.2*** it can be seen that the same bench may be represented several times and the detail of this is presented in ***Table 3.1***.

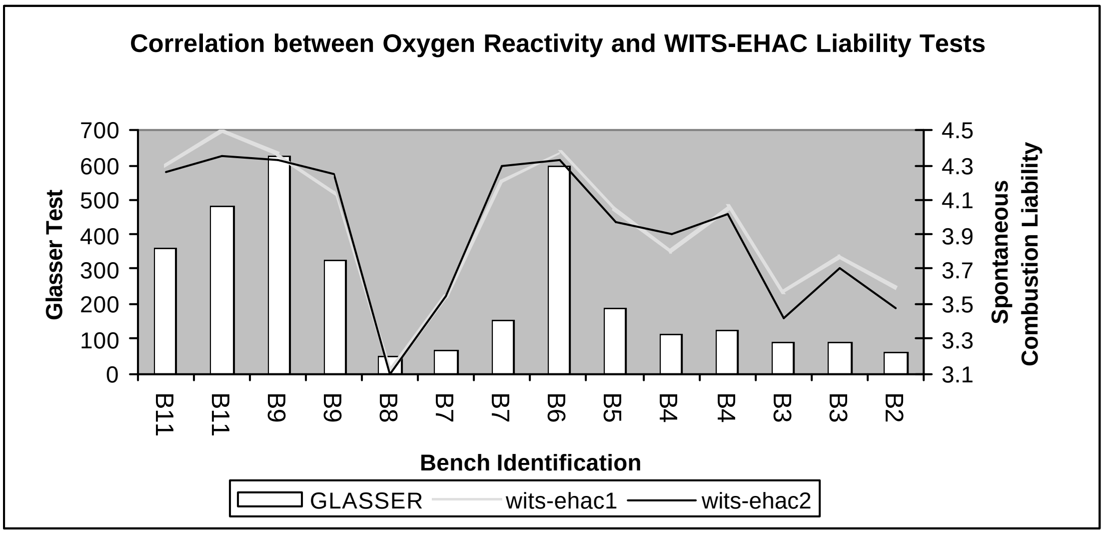


Figure 3.2: Waste Reactivity per Bench

A comparison of the reactivity results, representing waste material from each bench, obtained from the results of the WITS-EHAC liability tests and the Glasser oxygen reactivity tests, is shown in ***Figure 3.2***.

The WITS-EHAC test was carried out twice for each sample. The waste from benches 3, 4, 9 and 11 represented two different types of waste depending on cut RD (see cut RD and fraction in ***Tables 3.1 and 3.2***), representing the GG beneficiation process, while the bench 7 waste represented two types of waste: without beneficiation (as an inter-burden waste) and after beneficiation of GG2.

Bench	Fraction	Cut RD	Moist [%]	Ash [%]	Vol. [%]	S [%]	CV [MJ/kg]	Pyrite Sulphur [%]
B 1A	-6.5	-	1.8	71.8	17.3	1.42	6.92	1.21
B 2	-35	1.95	1.8	79.4	13.3	1.59	3.72	1.35
B 2	-12.5	1.85	3.7	81.4	12.6	1.32	2.53	1.18
B 3	-35	1.95	1.8	81.9	10.7	0.75	2.34	0.57
B 3	-12.5	1.85	1.8	74.6	13.6	0.91	4.86	0.80
B 4	-35	1.95	1.2	73.9	13.5	0.79	5.39	0.60
B 4	-12.5	1.85	2.2	74.0	13.4	1.80	5.66	1.58
B 5	-35	1.95	1.5	69.8	15.0	0.51	5.99	0.40
B 6	-35	-	1.6	36.5	22.6	2.59	19.26	2.12
B 7	½ (-35)	1.95	1.3	77.0	12.9	0.30	2.20	0.23
B 7	½ (-6.5)	-	1.3	67.9	15.1	0.24	6.45	0.20
B 8	-6.5	-	1.2	78.2	11.7	0.25	2.72	0.17
B 9A	-35	1.55	1.6	44.1	18.7	3.76	15.84	3.33
B 9B	-35	1.46	1.4	31.2	19.7	2.83	20.93	2.18
B 9B	-35	1.64	1.1	47.2	19.2	9.10	14.99	8.32
B 11	-35	1.41	1.6	12.2	24.9	0.93	28.83	0.20
B 11	-35	1.54	1.1	44.5	18.9	6.51	17.32	4.31

Table 3.1: Chemical and Physical Properties of Drill Core Material per Bench

All the correlating factors of waste reactivity, namely chemical and physical properties as well as petrography, obtained by standard geological tests are summarised in ***Tables 3.1 and 3.2***.

Bench	Fraction	Cut RD	Vitrinite [%]	Exenite [%]	Inert [%]	Minerals [%]	Reactive [%]
Bank 1A	-6.5	-	53.3	0.6	3.6	39.2	57.2
Bank 2	-35.0	1.95	30.0	0.5	14.8	43.3	41.9
Bank 2	-12.5	1.85	23.1	1.4	16.0	44.3	39.7
Bank 3	-35.0	1.95	11.4	0.3	32.2	44.4	23.5
Bank 3	-12.5	1.85	15.2	0.9	28.6	40.5	30.9
Bank 4	-35.0	1.95	12.2	1.5	32.3	40.1	27.6
Bank 4	-12.5	1.85	17.9	2.1	23.2	40.4	36.3
Bank 5	-35.0	1.95	5.0	0.0	50.4	37.8	11.8
Bank 6	-35.0	-	14.8	5.6	37.2	20.5	42.3
Bank 7	½(-35)	1.95	1.8	1.2	55.1	41.5	3.4
Bank 7	½(-6.5)	-	4.4	5.7	47.8	36.8	15.4
Bank 8	-6.5	-	1.7	0.0	55.7	42.3	2.0
Bank 9A	-35.0	1.55	3.8	0.0	66.1	24.7	9.2
Bank 9B	-35.0	1.46	3.3	0.8	73.4	17.7	8.9
Bank 9B	-35.0	1.64	2.8	0.0	65.9	28.0	6.1
Bank 11	-35.0	1.41	22.5	1.1	35.4	6.9	57.7
Bank 11	-35.0	1.54	8.5	0.7	51.1	25.8	23.1

Table 3.2: Petrography of Drill Core Materials per Bench

It is immediately apparent that the waste material has a high volatile content and it is known that volatile content is one of the main contributory factors to reactivity and the spontaneous combustion of the waste dumps.

Reactivity / age function

The results from the Glasser and Strauss tests allowed comparisons of the reactivity of fresh waste material (Glasser test) with the reactivity of the same but aged waste material (Strauss test). The samples of the waste material used in the Glasser test were kept open, allowing the oxidation of the samples, and then tested using the Strauss test. An analytical correlation between the Glasser test and the Strauss test for different ages of the same sample (see tests results in ***Table 3.3***) allowed the development of the following-empirical formula [3.1]. The curve is plotted for the waste material representing three benches (data in ***Table 3.3***) in ***Figure 3.3*** and the carver fitting technique has been used.

SAMPLE	Reactivity [ml O_2/kg/day]								
Bench ID	Glasser	Strauss							
	Fresh	12 days	19 days	21 days	25 days	32 days	34 days	47 days	50 days
9B	626	136		79			49	35	
6	599	132							29
11	484	84	64		45	44			
9A	425	109		64			37	26	
11	359	46	39		27	31			
9B	325	83		42			28	30	
5	191	38		23			13	13	
1A	164	40	38		28	25			
7	151	26		26			16	13	
7	145	13	11		7	9			
4	122	39		21			13	12	
4	112	35		21			13	11	
3	92	25		15			8	9	
2	58	12	13		10	11			
8	48	9	9		4	6			

Table 3.3: Correlation between Glasser and Strauss Tests, Age Function

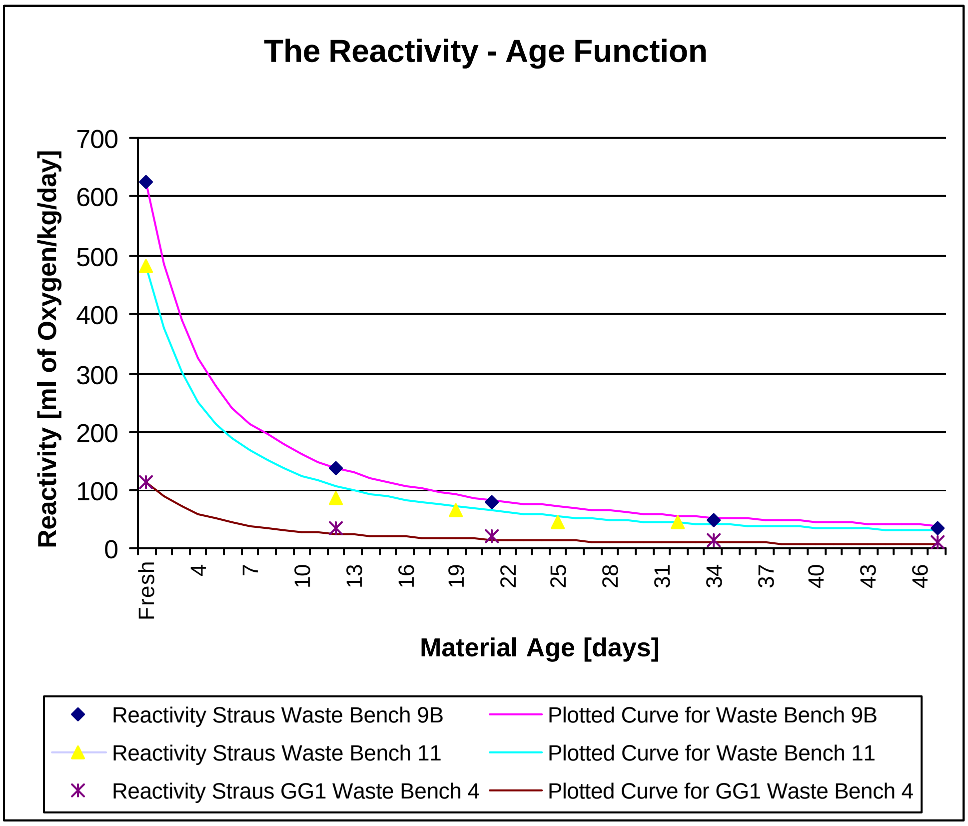


Figure 3.3: Reactivity - Age Function for Benches 9B, 11 and 4

The relationship obtained is
$R_t = R_{Glasser} (3t + 1) / (t + 1)^2$ [3.1]
Tests at temperature 35 ^{0}C, where:
R_t - Strauss, large-scale test as a function of time t [ml 0_2/kg/day]
$R_{Glasser}$ - Glasser, small-scale test for fresh coal reactivity [ml 0_2/kg/day]
t - age of coal [days]

Plant discard reactivity simulation
Results shown in ***Figure 3.2 and Tables 3.1 and 3.2*** represent all possible waste types present in each bench. However, in practice, plant discards can have different properties because the input rates from different benches are variable due to operational availability. The possible properties of plant discards are dependent on the availability of shovels in the pit and GG plants. Plants are affected by planned and unplanned maintenance. All the plants discard material is discharged into one stockpile from which one conveyor system transfers the discards to the stacking system. As discussed earlier, Grootegeluk Coal Mine has five plants, with GG4 and GG5 being interdependent in terms of operation. Therefore, in this analysis, four plants are considered, GG1, GG2, GG3 and GG4/5, and the properties of the individual plants and the probability of their contribution to the waste output are determined.

The four independent plants can result in 15 different properties of plants discards. The 15 probable combinations were monitored over almost one year (252 working days). The mixture of ROM material from each bench to each plant was determined according to the actual results derived from using the GG dispatch satellite system and compared to the production budget. The associated probabilities of these occurrences were obtained and considered by analysing the fluctuation in reactivity of the plant discards. The probability of each combination was calculated according to the statistical data obtained following the completion of the GG5 plant.

Results shown in ***Figure 3.2 and Tables 3.1 and 3.2,*** representing each bench, were then modelled according to the mixture of ROM material to each plant (plant input) obtained from using the GG dispatch system during the 252 days of monitoring.

In ***Table 3.4*** the contribution to plant waste (Mt) from each bench was found by monitoring the input to each plant over the 252 day period and calculating the waste output using a geological model of coal quality for each bench, which is dependent on beneficiation and monitoring of the plant output (product) over the same 252 day period. This way per cent contribution to total waste from each bench, resulting from each plant's beneficiation, was found, e.g. dependent on whether all plants were running (***Table 3.4***). Item B5 (waste from bench 5 resulting from beneficiation of bench 5 ROM in GG2) will contribute 23 % to the total waste produced by all GG plants.

Product Ash [%]	GG	Waste		Bench	Cut RD	Moist. [%]	Ash [%]	Volatile [%]	S [%]	Pyrite [%]	CV MJ/kg	Reactivity ml02/kg/day
		[Mt] 252 days	[%]									
<35	GG2	0.62	4	B2	>1.95	1.8	79.4	13.3	1.59	1.35	3.72	58
<10	GG1	2.77	17	B2	>1.85	3.7	81.4	12.6	1.32	1.18	2.53	58
<35	GG2	0.69	4	B3	>1.95	1.8	81.9	10.7	0.75	0.57	2.34	92
<10	GG1	3.13	19	B3	>1.85	1.8	74.6	13.6	0.91	8.00	4.86	92
<35	GG2	0.69	4	B4	>1.95	1.2	73.9	13.5	0.79	0.60	5.39	112
<10	GG1	3.05	19	B4	>1.85	2.2	74.0	13.4	1.80	1.58	5.66	122
<35	GG2	3.86	23	B5	>1.95	1.5	69.8	15.0	0.51	0.40	5.99	191
<35	GG3	0.19	1	B6	ROM	1.6	36.5	22.6	2.59	2.12	19.26	599
<35	GG2	0.37	2	B7	>1.95	1.3	77.0	12.9	0.30	0.23	2.20	145
<10	GG4/5	0.37	2	B9	>1.46	1.4	31.2	19.7	2.83	2.18	20.93	626
<15	GG4/5	0.31	2	B9	>1.64	1.1	47.2	19.2	9.10	8.32	14.99	325
<10	GG4/5	0.24	1	B11	>1.41	1.6	12.2	24.9	0.93	0.20	28.83	484
<15	GG4/5	0.16	1	B11	>1.54	1.1	44.5	18.9	6.51	4.31	17.32	359
Results		**16.45**	**100**			**2.1**	**71.9**	**14.1**	**1.3**	**2.5**	**5.9**	**146.4**

Table 3.4: Plant Discards Properties while all Plants are running

Case	Probability	RD	Ash	Volatile	S	Pyrite	CV	Glasser / Wits-ehac
Plants standing While the rest run	From 0 to 1	Cut Point	[%]	[%]	[%]	[%]	MJ/kg	
GG2 & 3 & 4/5	0.0040	>1.85	76.50	13.22	1.34	3.70	4.41	91.70 / 3.7
GG2 & 4/5	0.0000	>1.8	75.67	13.42	1.37	3.67	4.72	102.20 / 3.7
GG3 & 4/5	0.0040	>1.85	75.05	13.57	1.06	2.40	4.68	117.80 / 3.8
GG4/5	0.0635	>1.8	74.58	13.68	1.08	2.39	4.86	123.80 / 3.8
GG2 & 3	0.0000	>1.41	71.87	14.02	1.71	3.71	6.14	132.30 / 3.8
GG2	0.0079	>1.41	71.22	14.18	1.72	3.68	6.38	140.90 / 3.8
GG3	0.1111	>1.41	72.30	14.03	1.31	2.49	5.73	141.10 / 3.8
All running	0.7579	>1.41	71.88	14.13	1.32	2.49	5.88	146.40 / 3.8
GG1 & 3 & 4/5	0.0000	>1.95	72.98	14.06	0.66	0.53	5.07	155.30 / 3.8
GG1 & 4/5	0.0000	>1.8	71.90	14.32	0.72	0.57	5.49	168.40 / 3.8
GG1 & 3	0.0000	>1.41	67.15	15.03	1.27	1.01	7.34	201.60 / 3.9
GG1	0.0159	>1.41	66.37	15.22	1.30	1.04	7.64	211.70 / 3.9
GG1 & 2 & 3	0.0000	>1.41	33.54	20.59	4.75	3.82	20.45	468.49 / 4.3
GG1 & 2	0.0079	>1.41	33.98	20.89	4.43	3.56	20.27	488.02 / 4.3
GG1 & 2 & 4/5	0.0000	>1.8	36.50	22.60	2.59	2.12	19.26	599.00 / 4.3
All standing	0.0278							

Table 3.5 Discards Properties for all 15 Probable Cases

The reactivity and correlated reactivity factors, obtained from the standard geological tests, representing each bench were analysed and modelled using the determined per cent contributions to represent the properties of the 15 possible discard mixtures.

The final reactivity figure and figures for the correlating factors in this model were obtained by taking the weighted average (see " Results" for "All Plant Running in ***Tables 3.4***).

It was important to summarise the properties of the 15 mixtures according to the probability of the occurrence of each mixture. In ***Table 3.5***, all these cases are summarised (from lowest to highest reactivity of mixtures) with the associated probability of occurrence of each mixture monitored during the 252 days. The factors for the main properties illustrated in ***Table 3.5*** are shown in ***Figure 3.4***.

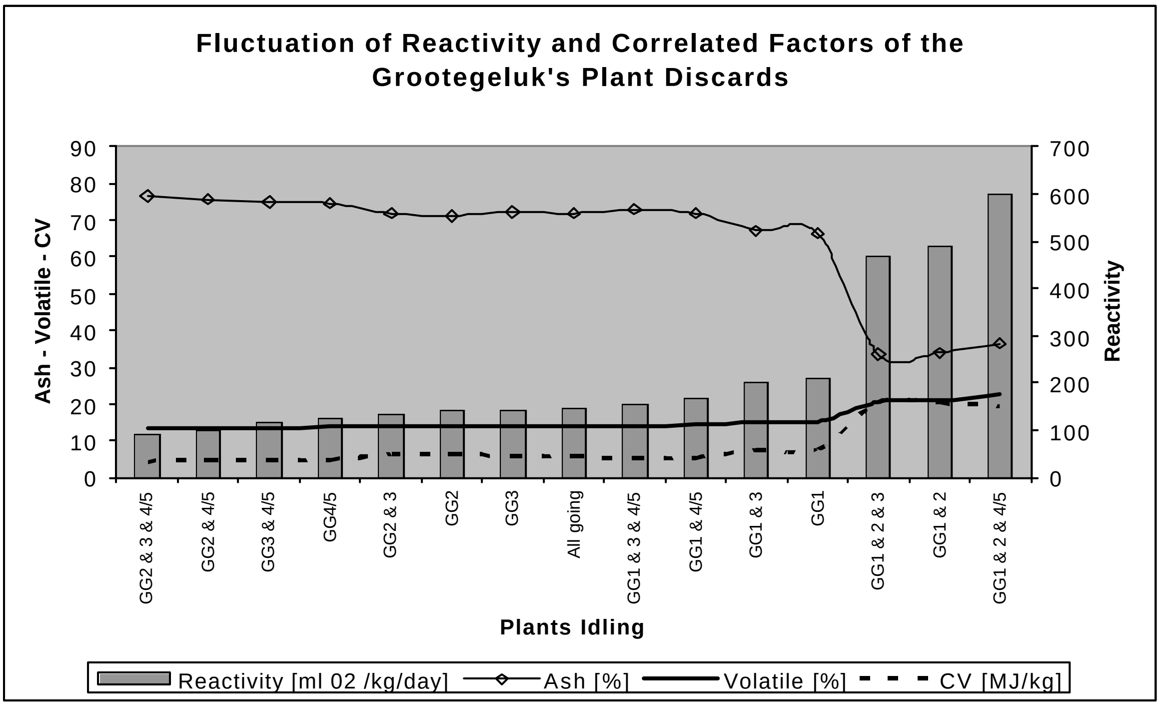


Figure 3.4: Correlation between Various Properties of Plant Discards

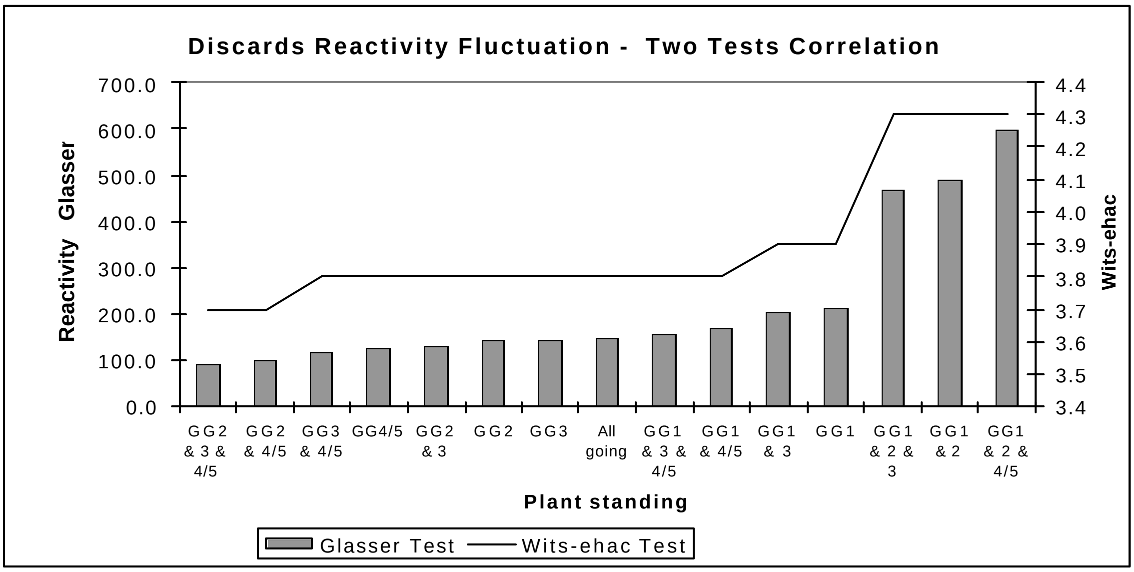


Figure 3.5: Correlation between WITS-EHAC and Glasser Tests for Plant Discards Reactivity

The correlation in the modelled reactivity fluctuation between the Glasser test and the WITS-EHAC test for the 15 discard mixtures is shown in ***Figure 3.5***.

Summary of Findings

The wide range in the chemical and physical properties of the discard material obtained from different benches (B1 – B11) is illustrated in the results above. Waste from benches 9B and 6 is found to be the most reactive according to the Glasser test, namely about 600 cm^3 of O_2 absorbed per kg coal per day. A good correlation in general was also found between the oxygen-absorption-reactivity Glasser test and the WITS EHAC liability test (which was used for verification purposes). Correlations between reactivity and other chemical and physical properties, especially volatility, were also found.

Very good correlation was found between the various properties of the mixtures, as illustrated in ***Figure 3.3***. As expected, materials with a high reactivity were those that had low ash content, higher volatile matter and high calorific values. The probability of finding these different mixtures in practice is also shown on the graph ***Figure 3.3***. It is proved by the 252 day survey that the probability of finding the mixture with all plants operating is the highest (75.79 %).

Plant mixtures with the lowest reactivity, as measured by the oxygen-absorption Glasser test and the WITS-EHAC index, were found for plants GG-2, 3 and 4/5 standing (only GG1 running) and also for plants GG-2 and 4/5 standing (GG1 and GG3 running). The probability of finding these mixtures in practice is, however, very low (***see Table 3.19***).

The mixtures with the highest oxygen reactivity were mixtures with GG-1 and 2 standing (GG3 and GG4/5 running), GG-1, 2 and 3 standing (GG4/5 running) and GG-1, 2 and 4/5 standing (GG3 running). The probability of finding these mixtures in practice is also very low. A high probability was also found for plant GG-3 standing (GG1, 2 and 4/5 running) and the highest probability is for all plants running. The mixtures obtained for the high probabilities were of intermediate reactivity with regard to oxygen absorption.

3.3.2 Column Tests

As discussed earlier in this chapter, it was essential to obtain information regarding the best sealing material, the effect of sealing material thickness and the influence of the same sealing material on materials of different reactivity. Therefore, the column tests were prepared in such a way to enable the determination of the best sealing material and to determine all the effects necessary to develop a mathematical model of the sealing process.

General description of column tests

Various materials were considered, as discussed earlier, for their suitability as a sealing layer over waste heaps, namely: Grootegeluk weathered overburden material, red sand, wet Grootegeluk weathered overburden material, dry Matimba ash, wet Matimba ash, and Grootegeluk dry and wet slurry.

By observing the depletion of oxygen at the contact of the sealing and reactive materials, the best sealing material was chosen. The temperature within the material was a constant 35 ^{0}C, controlled electronically. In total five tests were undertaken, using either three or four columns simultaneously in order to keep the parameters constant within a single test. The programme is specified in ***Table 3.6***.

Tests 1 and 2 (see ***Table 3.6***) used only three columns, while the fourth column was being constructed. Test 1 did not use reactive material at the bottom of the column. The objective of this test was to measure the permeability of Grootegeluk dry and wet overburden and red sand to air (see ***Table 3.6***). The three materials were placed in the three columns respectively, and all columns were 3 m high. The columns were then flushed with nitrogen after which time the oxygen level was monitored along the columns. Through this method, the most permeable of the materials was identified and eliminated, i.e. the red sand was found to be not suitable.

Test 2 used crushed and selected –32 mm discards from GG4/5 plant. It was found that the reactivity of this material was too low to measure, i.e. it was impossible to observe the oxygen depletion efficiently, and it was then decided to use the 10 % coking coal product at the bottom of columns.

The first three tests focused on the selection of the best material for the sealing purpose. The following two tests concentrated on the effect of sealing material thickness on the same reactive material and the influence of the same sealing material on materials of different reactivity to determine the mathematical sealing model.

All test details are described in ***Table 3.6.*** From this table, all the information can be obtained regarding the type and thickness of reactive material at the bottom of each column and the thickness and type of the sealing material used at the top of each column. The results of each test are discussed in detail below.

Test	Column	Sealing Material – top of the column		Reactive Material – bottom of the column	
		Type	Layer [m]	Type	Layer [m]
Test 1	A	Weathered Overburden	3	None	0
	B	Weathered Overburden Wet & Compacted	1.5 1.5	None	0
	C	Red sand	3	None	0
Test 2	A	Weathered Overburden	2	-32mm GG4/5 discards	1
	B	Weathered Overburden Wet & Compacted	2	-32mm GG4/5 discards	1
	C	Dry Matimba Ash	2	-32mm GG4/5 discards	1
Test 3	A	Weathered Overburden Wet & Compacted	2	Product 10 % ash product	1
	B	Wet Matimba Ash	2	Product 10 % ash product	1
	C	Liquid slurry Weathered Overburden	1 1	Product 10 % ash product	1
	D	Dry slurry Weathered Overburden	1 1	Product 10 % ash product	1
Test 4	A	Weathered Overburden Wet & Compacted	0.5	Product 15 % ash product	1
	B	Weathered Overburden Wet & Compacted	1.0	Product 15 % ash product	1
	C	Weathered Overburden Wet & Compacted	1.5	Product 15 % ash product	1
	D	Weathered Overburden Wet & Compacted	2.0	Product 15 % ash product	1
Test 5	A	Weathered Overburden Wet & Compacted	2	Product 10 % ash	1
	B	Weathered Overburden Wet & Compacted	2	Plant discards while all plants running	1
	C	Weathered Overburden Wet & Compacted	2	ROM Bench 7A	1
	D	Weathered Overburden Wet & Compacted	2	ROM Bench 8	1

Table 3.6: Description of Column Tests

Test 1

This column test was performed to compare the air permeability of weathered overburden material (both dry and wet compacted) and red sand. Overburden material was tested dry, as loaded by shovels, and wet with slight surface compaction, using a wooden stick for this purpose. In this case, three columns were used. Each column was filled with the respective material without any reactive material at the bottom. Columns were flushed with nitrogen and the air transportation from the top to the bottom of each column was measured by monitoring the oxygen level in the columns over a 24 day period. The best material, in terms of its sealing ability, would be the one where the oxygen percentage at each sampling point increases the slowest.
The same data has been re-plotted to illustrate the sealing properties of the three materials and is shown in ***Figure 3.6***

The wet compacted overburden material has the best sealing property. The mined overburden material has a slightly worse sealing property than the wet compacted on-surface overburden material. The wet compacted overburden material was tested as a sealing material to determine any change in properties due to the impact of rainfall and surface compaction by running equipment. It was essential to establish this difference to take account of more realistic conditions. Red sand was found to be very permeable and the worst of the inert materials available for sealing purposes at Grootegeluk mine and was therefore excluded.

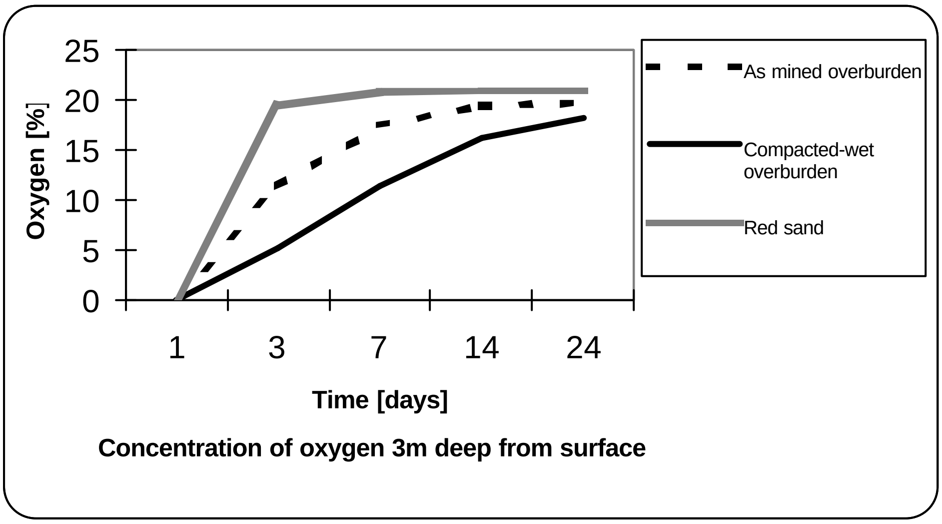


Figure 3.6: Column Test 1 Results Summary

Test 2

The purpose of this 67 day test was to compare the sealing properties of overburden material and power station ash when placed over 1 m of reactive material (***see Table 3.6***). In this test three columns were used. Each column was filled with crushed and selected -32 mm GG4/5 discard material, 1 m high at the bottom of the each column and covered by a 2 m thick sealing layer of dry and wet overburden and dry Matimba ash, respectively. The columns were flushed with nitrogen and the oxygen transportation from the top to the bottom of each column was measured by monitoring oxygen depletion in the columns.

Since the test was designed to evaluate the sealing properties of the inert material, lower flow rates of oxygen and hence lower concentrations in the reactive material could be used as a means of ranking the sealing properties.

A summary of Test 2 is shown in ***Figure 3.7***. The wet-compacted overburden material has the best sealing property of the tested materials. Even though the dry Matimba ash showed worse sealing properties than the overburden material, it was essential to test the same material exposed after moisture absorption. The Matimba ash showed a change in properties after a few weeks from “powder to concrete”, as can be seen by an inspection of the Matimba ash dump. The friable powder exposed to moisture or water (rain) changes to cake and then to concrete. It was essential, therefore, to check the sealing properties of the wet Matimba ash and this was done in the next test.

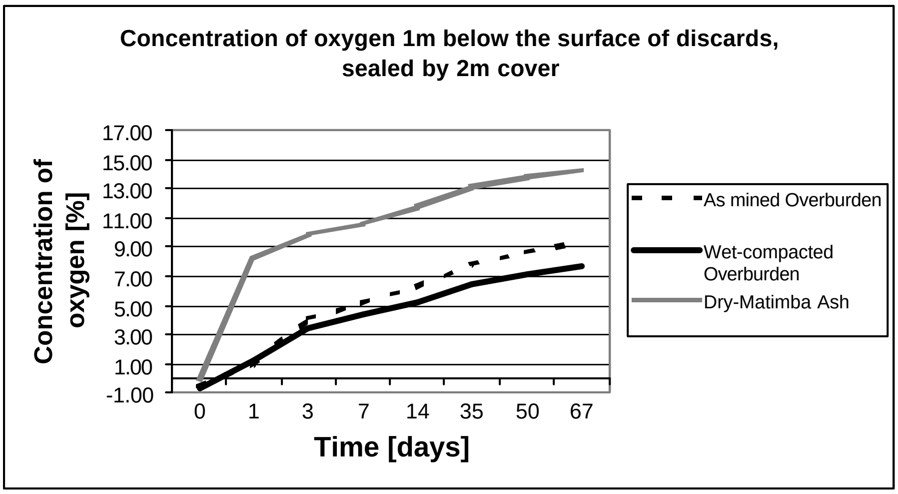


Figure 3.7: Column Test 2 Results Summary

Test 3

The purpose of this 223 day test was to compare the sealing properties of wet overburden material, wet Matimba power station ash, dry coal slurry and liquid coal slurry (***see Table 3.6***). By the time of this test, the fourth column was available. The 10 % ash coking coal product was used as the reactive material at the bottom of each column to obtain better depletion of oxygen. The liquid and the dry coal slurry were used on top of the overburden material to simulate practical operational conditions. Placing liquid coal slurry on top of coal material could cause sinking of the slurry into this material. Therefore, the reactive material was covered, where coal slurry was used, by a 1 m thick layer of overburden and then by a 1 m thick layer of coal slurry: liquid and dry respectively. During the first few days of the test, leakage of air at the contacts between columns' segments was found within columns C and D. This leakage was immediately sealed.

Wet slurry had the best sealing properties as shown in ***Figure 3.8***, which summarises this test.

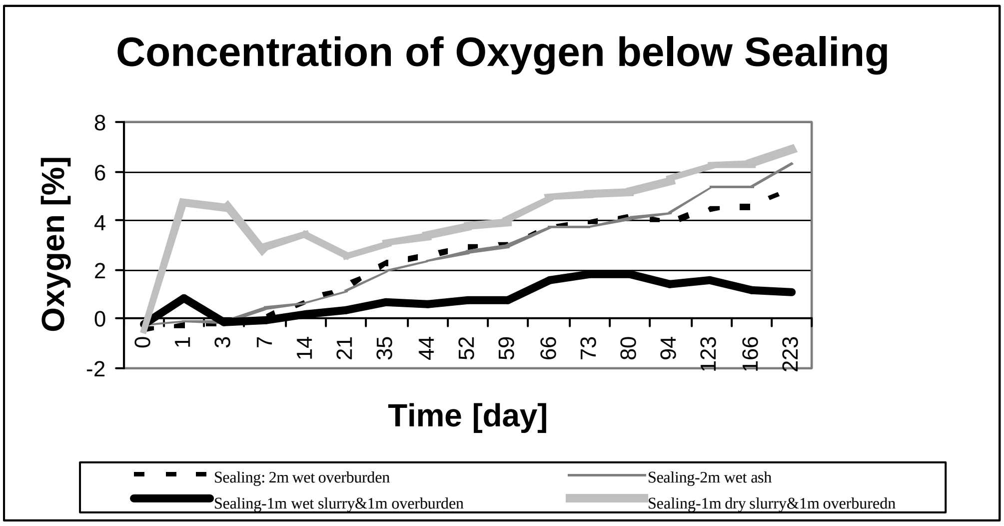


Figure 3.8: Column Test 3 Results Summary

Although not indicated in a 223 day test, there is a high risk under normal operating conditions that the good sealing properties of wet coal slurry will be lost as the material dries and cracks, while the coal slurry becomes less reactive and dry. It can be assumed that the sealing properties of the wet slurry will change and in time they will become similar to the properties of the dry slurry.

Unlike the mechanism created by the other sealing materials, which rely on their permeability and porosity, at least part of the sealing characteristics of the coal slimes are due to their reaction with the oxygen in the air passing through, thereby depleting the oxygen content.

The wet Matimba ash and the wet Grootegeluk overburden have the same sealing properties. Taking into account the cost and infrastructure necessary for the placement of liquid coal slurry and/or for transportation of Matimba ash, weathered overburden material is recognised as the best material for the sealing model at Grootegeluk Coal Mine.

Test 4

Having decided on overburden as the best sealing material, the next 29 day test focused on the relationship between oxygen depletion and the sealing thickness of overburden material (***see Table 3.6***). A 15 % product was used as the reactive material to determine the difference in oxygen depletion between the 10 % and 15 % ash product.

Results of this experiment show an almost linear function between oxygen depletion at the contact between the reactive and sealing materials and overburden thickness (see ***Figure 3.9***). This linear function means that a 3.5 m thick layer of overburden sealing would store a 15 % ash product safely at about 35 ^{0}C. In this case, the supply oxygen is limited and, at the contact layer between the inert and reactive material, it is absorbed immediately.

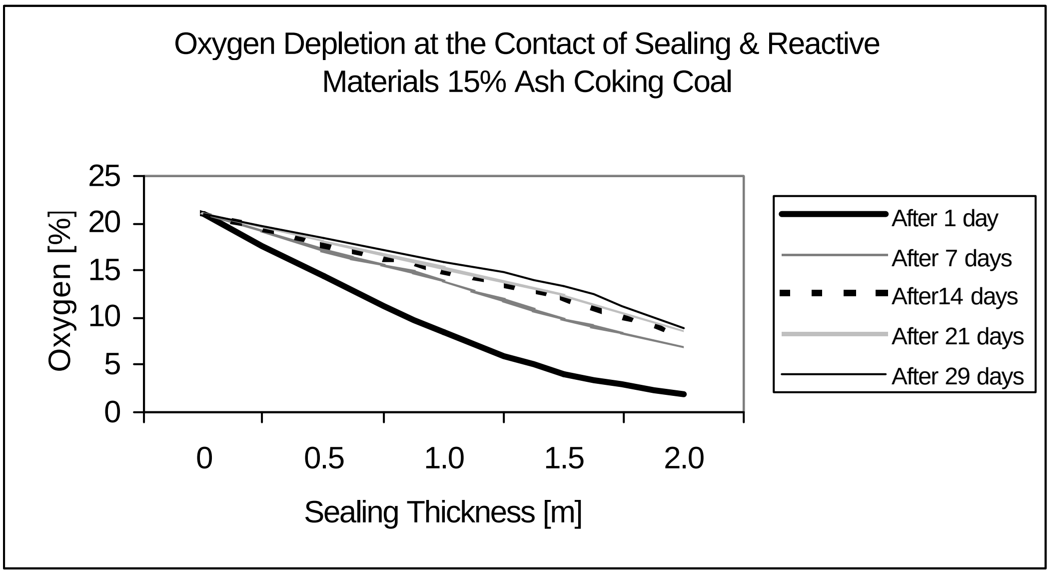
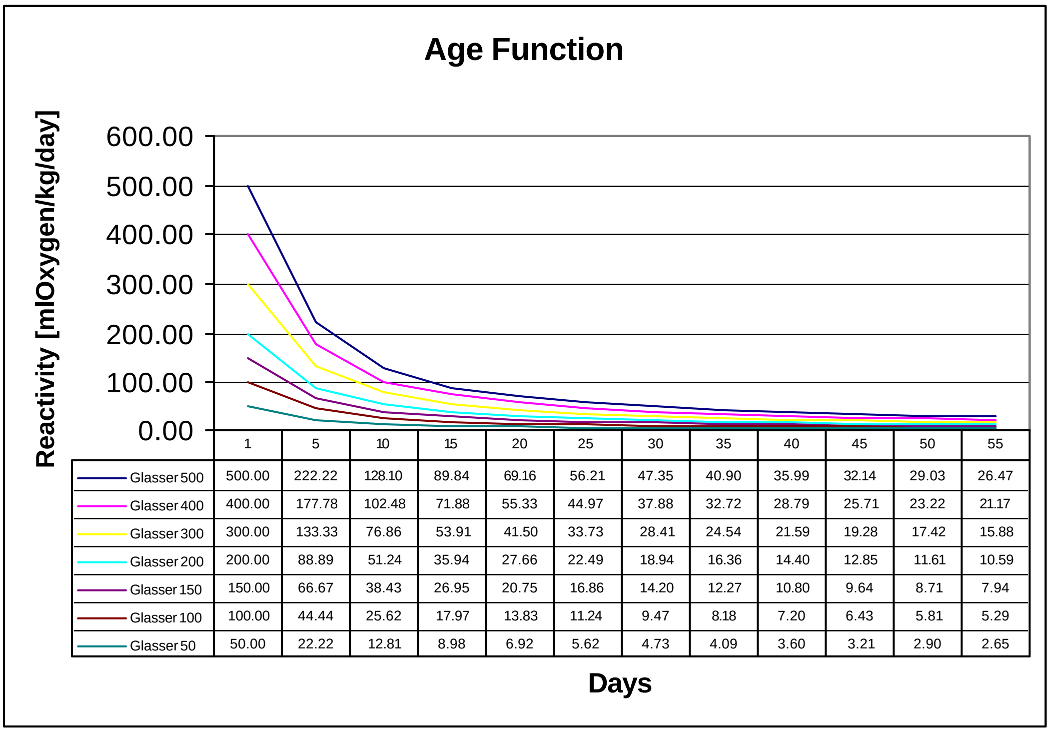


Figure 3.9: Column Test 4 Results Summary

However, adding the age function, equation [3.1] (see ***Figure 3.10***), the reactivity of the material immediately below the seal would decrease in time allowing oxygen to penetrate deeper into the reactive material.

Figure 3.10 shows a reduction in reactivity with time for different reactive materials, assuming a dissipation of heat to allow a constant temperature of 35 ^{0}C and available oxygen for cold oxidation. Grootegeluk waste materials are found to be in the reactivity range illustrated in ***Figure 3.10.***



	1	5	10	15	20	25	30	35	40	45	50	55
Glasser 500	500.00	222.22	128.10	89.84	69.16	56.21	47.35	40.90	35.99	32.14	29.03	26.47
Glasser 400	400.00	177.78	102.48	71.88	55.33	44.97	37.88	32.72	28.79	25.71	23.22	21.17
Glasser 300	300.00	133.33	76.86	53.91	41.50	33.73	28.41	24.54	21.59	19.28	17.42	15.88
Glasser 200	200.00	88.89	51.24	35.94	27.66	22.49	18.94	16.36	14.40	12.85	11.61	10.59
Glasser 150	150.00	66.67	38.43	26.95	20.75	16.86	14.20	12.27	10.80	9.64	8.71	7.94
Glasser 100	100.00	44.44	25.62	17.97	13.83	11.24	9.47	8.18	7.20	6.43	5.81	5.29
Glasser 50	50.00	22.22	12.81	8.98	6.92	5.62	4.73	4.09	3.60	3.21	2.90	2.65

Figure 3.10: Reactivity Age Function

The flow rate of oxygen transported could be assumed to be constant, as discussed above, due to the constant sealing property which allows only a fixed volume of air to be transported into a dump.

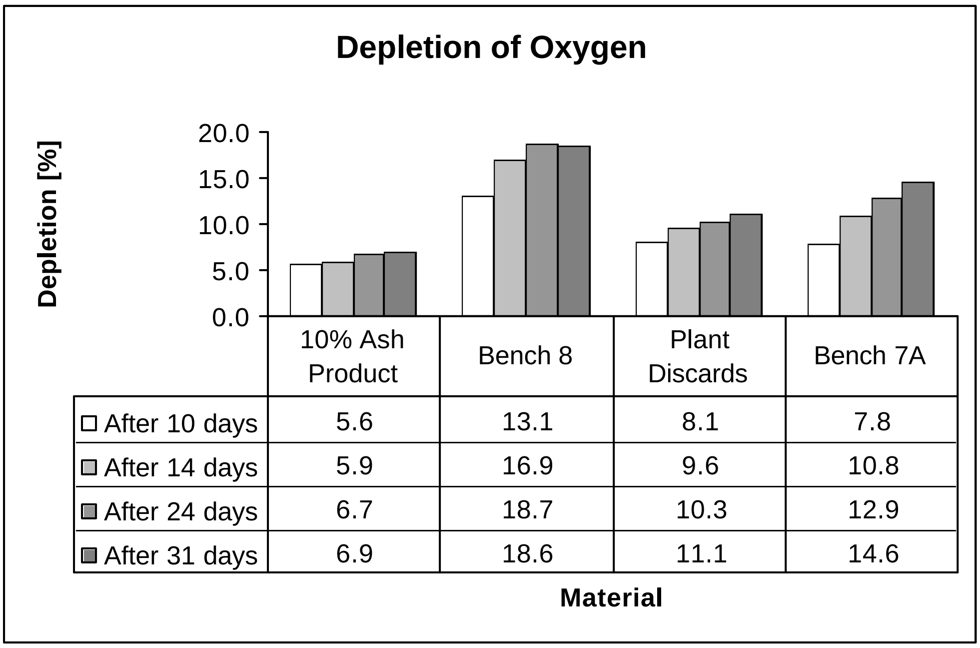
Therefore, it could be concluded that the reaction rate would also remain constant, causing no temperature increase at a constant reactivity of material. Should the temperature increase because the reaction is taking place deeper inside the dump, the overlying material would also increase in temperature and become more reactive. This would mean that oxygen depletion will again take place at a shallow level. The temperature would stabilise at a level at which the low reactive material would become again more reactive and would react at the same rate as the 15 % ash product. At some stage of the age function effect, the equilibrium of heat dissipation and heat generation would occur. The rate of the heat dissipation might be higher than the rate of the generated heat, and the reducing reactivity due to the age function would cause a temperature reduction in time.

Test 5
Having established the best sealing material and the relationship between seal thickness and oxygen depletion, the final 31 day test focused on depletion of oxygen within different Grootegeluk waste materials, sealed by the same thickness of the selected overburden material (***see Table 3.6***). The reactive materials used were 10 % ash coking coal product, plant discards while all plants were running, bench 7A inter-burden and bench 8 inter-burden.

This test allowed a sealing model to be built to identify the necessary sealing layers of the overburden material required to deplete oxygen to zero within the different types of waste materials at Grootegeluk. The results are summarised in ***Figure 3.11***.

Through column testing, an effective method was found to select a sealing from the overburden layers capable of restricting oxygen inflow into a dump to the level where oxygen will be depleted to zero at the contact with the reactive material. It is evident from ***Figure 3.11*** that the lower the reactivity, the less the oxygen depletion.

Therefore, lower reactive materials would require a thicker layer of overburden sealing to deplete the oxygen to zero at the contact between the sealing layer and the reactive material. Although this may be unexpected, the test results have proven that the more reactive the material, the quicker a limited flow of oxygen will be depleted.



	10% Ash Product	Bench 8	Plant Discards	Bench 7A
☐ After 10 days	5.6	13.1	8.1	7.8
☐ After 14 days	5.9	16.9	9.6	10.8
☐ After 24 days	6.7	18.7	10.3	12.9
☐ After 31 days	6.9	18.6	11.1	14.6

Figure 3.11: Column Test 5 Results Summary

3.4 Sealing Model

Using the results of the oxygen depletion at the contact of different reactive materials and 2 m overburden sealing layers (tests 4 and 5), a sealing model was established that used a linear function between oxygen depletion and the thickness of a sealing layer (see ***Figure 3.9***).

The sealing model, see ***Figure 3.12***, simulates the necessary sealing layers of overburden (material wet from rain and compacted by operating mining equipment) required to deplete oxygen to zero for sealing the different waste materials found at Grootegeluk and 10 % and 15 % Grootegeluk coal products. From this graph (***Figure 3.12***), the concentration of oxygen within the reactive materials can be found as a function of the sealing thickness.

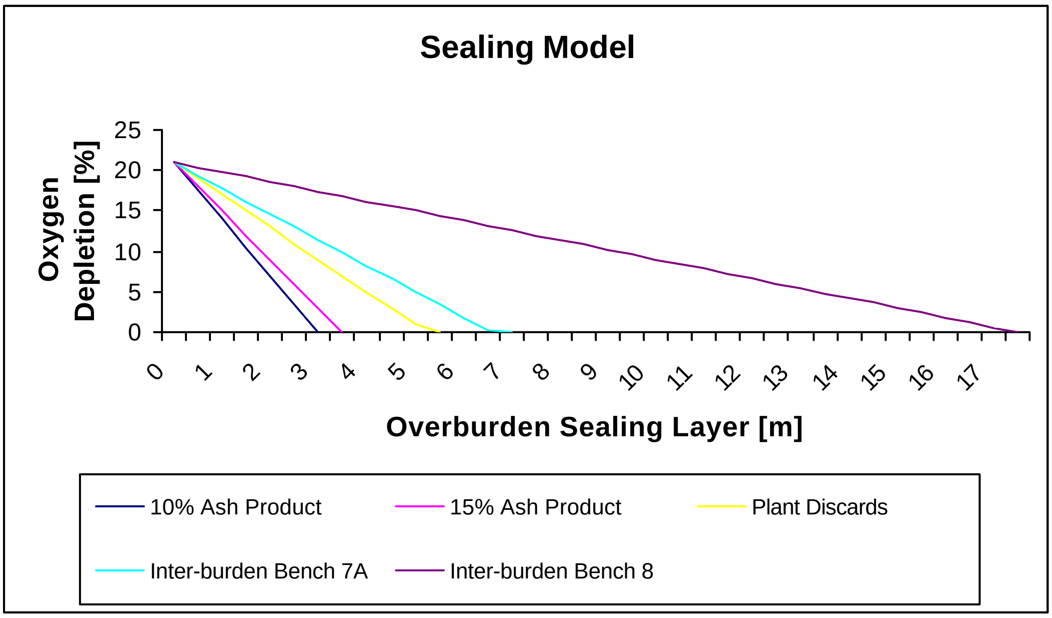


Figure 3.12: Sealing Model for Grootegeluk Waste Materials

4 MODELLING OF BACKFILLING METHOD USING SEALING THEORY AND RISK ASSESSMENT MODEL

The identified objective was to develop a method of storing reactive waste material within an enclosure made from inert material so as to prevent spontaneous combustion from creating a problem within the working open pit. It was considered that this could be achieved by obtaining a full bank of information from the laboratory testing required by the contributory model to establish the database mathematical risk model, as defined in Chapter 2. In order to construct a backfilling model, the sealing model was established, as detailed in section 3.5.

4.1 Theory of Sealing

It is not economically viable, due to the required thickness of the sealing material, to deplete the oxygen level of a low reactive material completely to zero at the contact between the sealing material and the reactive material. The available database has shown that, as the temperature increases, the material increases its reactivity in terms of oxygen absorption (reactivity doubles every 10 ^{0}C). In the case of a low reactive material sealed by a thinner than the required layer (according to the Sealing Model), the available oxygen would cause the temperature to increase within the reactive material. The increase in temperature will cause an increase in the reactivity of such material. The temperature will stabilise at a level that depends on several factors. Reactivity, which is temperature dependent, will obviously be important. Thickness and hence insulating properties of the sealing material will also affect this situation. Finally, the oxygen flow, which is dependent on the permeability of the sealing material, is also important. Limited oxygen due to limited air flow will not allow an increase in the oxidation rate. Reaction rate will stabilise at a constant temperature level, depending on the above-mentioned equilibrium between heat dissipation and generation. Taking the age function into account, i.e. the depletion of reactivity with time, the temperature will decrease when the heat dissipation rate is higher than the rate of the generated heat.

It is possible that the temperature will not rise to the level discussed above for very low reactive material. The heat generation of very low reactive waste material, such as that from Bench 8, could be much lower than the heat dissipation. This means that the temperature would not increase. However, this heat balance cannot be simulated and tested in a laboratory due to the heat losses. Therefore, the sealing model could only by tested during a large-scale test within the operating pit of Grootegeluk.

If temperature does increase during a large-scale test due to an error in the calculated thickness of the sealing layer, it can be controlled by increasing this thickness. The heat exchange cannot be modelled. It can only be found empirically during a large-scale test. The reasonable thickness of the sealing layer for all Grootegeluk waste must be economical and practical considering the stripping ratio of the pit. Therefore, it was decided to seal the surface of all types of Grootegeluk waste with a 3 m thick layer of overburden during the first large-scale test.

The consequences of such a decision are that, at some temperature, the lower reactive material will become just as reactive as the 10 % ash product which was tested and for which the 3 m thick sealing layer is sufficient. Therefore, the 3 m sealing layer should deplete the oxygen to zero at the contact of reactive waste with the sealing material. The difference for a lower reactive material will be only in the temperature, which will stabilise within the sealed compartments depending on the reactivity. Plotted temperatures within the different waste materials, neglecting the age function, are shown in ***Figure 4.1.***

The reactivity of the 10 % ash product is close to 1 000 ml O_2/kg/day at 35 ^{0}C (Glasser). Therefore, the temperature should theoretically stabilise at the following temperatures:
For plant discards at 62 ^{0}C
For inter-burden benches 7A, 7B and 8 at about 65 ^{0}C
For inter-burden benches 7A and 8 at 75-80 ^{0}C - but this temperature increase may not occur due to the heat dissipation being greater than the heat generation for this low reactive material.

The large-scale test results were designed to find the real relationships contributed by the age function and the balance between heat generation and heat dissipation.

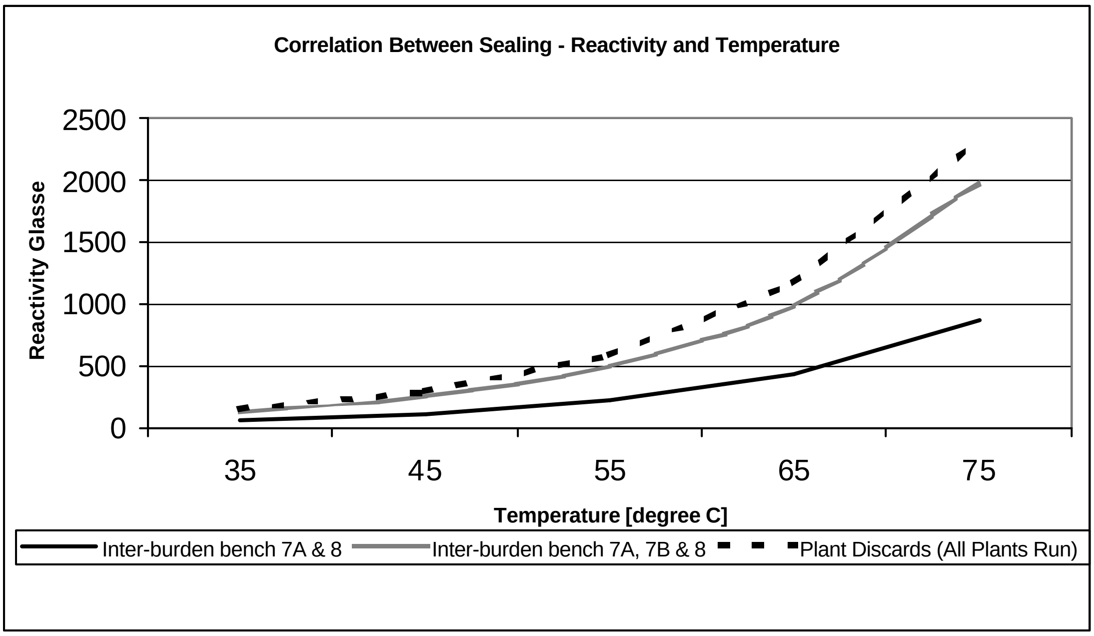


Figure 4.1: Calculated Temperature within Different Waste Material

4.2 Database Mathematical Risk Model

4.2.1 General Discussion

The Database Mathematical Risk Model (DMRM) was constructed using all the data discussed previously in this thesis, and from the updated database and recent tests results, and was based on the risk assessment model developed by Bystron & Urbanski. The factors listed in ***Table 4.1*,** namely the material, environmental and mining risk factors, were used as a guideline to construct the model that is used in this study.

Certain weights were assigned to each of these factors based on experience, both empirical and from observations of the laboratory tests. These values were further considered in the data available from previous large-scale tests at Grootegeluk. As the contribution (weight) of some of these factors may change with time, this aspect was taken into consideration during the construction of the model. The ranges of variation for each factor are shown in ***Table 4.2***. The weight for each single element varied from –10 to +10. The weight represents the contribution of each element towards the total risk of spontaneous combustion, which was calculated for each individual factor, each risk factor group and the overall risk. An example of the model is shown in ***Figure 4.2*.** The model also reflects the severity of individual parameters that contributes towards the overall risk. This feature helps to identify major factors that can contribute to self heating and may help engineers in the planning and design stage. The interpretation of the risk index is shown below in ***Table 4.1***.

Interpretation of the risk index	
-100 to -70	Definitely no risk
-70 to -40	Almost certain no risk
-40 to 0	Probably no risk
0 to 100	Slight evidence (0-50 no risk; 50-100 risk)
100 to 140	Probable risk
140 to 170	Almost certain risk
170 to 200	Definite risk

Table 4.1: Risk Index

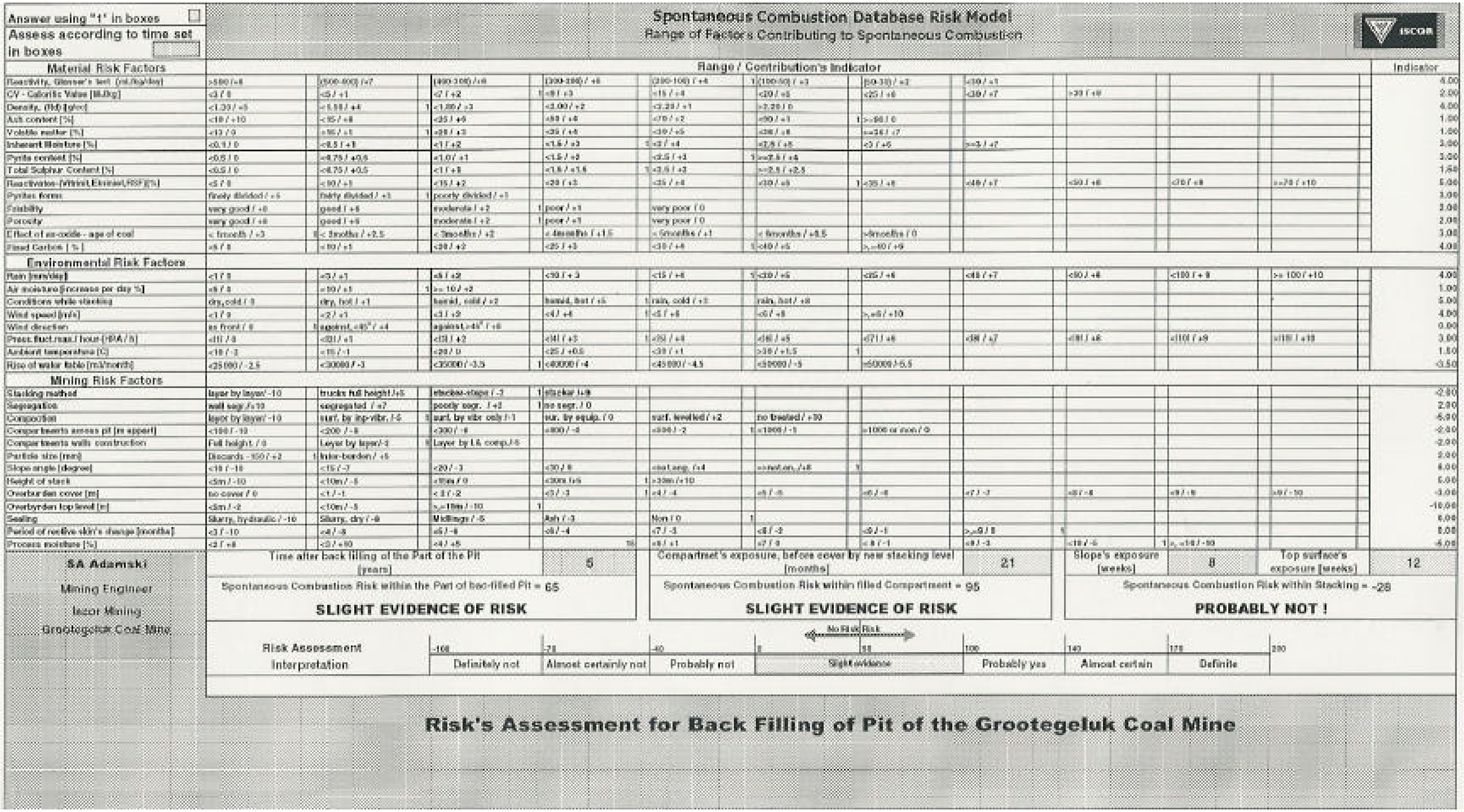
Some of the factors are, however, dependent on other factors, for example a continuous fluctuation in ground water level in a pit will cause the risk to vary from time to time. The risk of spontaneous combustion can range from “definitely not” (equal to the weight –100 points in the model), to “definite” (equal to the weight +200 points in the model), as a function of time. It is possible for the risk to increase, decrease or fluctuate with time, which depends on specific conditions and other contributing factors. For this reason, assumed formulae are included in the model to compensate for the time contribution factor because time changes the risk of spontaneous combustion from “definitely not” to “definite”. Therefore, the risk of spontaneous combustion is a function of time. This model aims to address the spontaneous combustion problem in terms of its risk and the model provides the solution in order to address this in the most suitable manner.

All these assumed formulae of the contribution of time are based on the experience of Grootegeluk Mine and on the available database.

The model was used to investigate the correlation of individual factors contributing to the risk of spontaneous combustion in the following three areas of investigation: stacking area, sealed compartment and rehabilitated pit.

Contributing factors to spontaneous combustion of the waste material at Grootegeluk	
Material Risk Factors (considering fluctuation of reactivity of Grootegeluk's Waste Material)	
Reactivity [ml 0_2/kg/day]	From 0 to more than 500
CV [MJ/kg]	From less than 3 to more than 30
Density, RD	From less than 1.3 to more than 2.2
Ash content [%]	From less than 10 to more than 90
Volatile matter [%]	From less than 13 to more than36
Inherent moisture [%]	From less than 0.1 to more 3
Pyrite content [%]	From less than 0.5 to more than 2.5
Sulphur content [%]	From less than 0.5 to more than 2.5
Reactivates (Vitrinite, Exinite and RSF) [%]	From less than 5 to more than 70
Pyrites forms	From "finally, through fairly to poorly" divided
Friability	From v/good, good, moderate, poor to v/poor
Porosity	From v/good, good, moderate, poor to v/poor
Effect of age [month]	From less than 1 to more than 6
Fixed carbon content [%]	From less than 5 to more than 40
Environmental Risk Factors	
Rain [mm/day]	From less than 1 to more than 100
Air moisture (increase per day) [%]	From less than 5 to more than 10
Conditions while stacking	From dry cold-hot, wet cold-hot, rain cold-hot
Wind speed [m/s]	From less than 1 to more than 6
Wind direction	From "as front, $<45^0$ to front, to $>45^0$ to front"
Pressure fluctuation [hPa/h]	From less than 1 to more than 10
Ambient temperature [^{0}C]	From less than 10 to more than 30
Ground water inflow [m^3/month]	From less than 25 000 to more than 50 000
Mining Risk factors	
Stacking method	From "layer by layer", trucks dumping, stacker steps to stacker full height stacking
Segregation	From well segregated, segregated, poorly segregated to not segregated
Compaction	From "layer by layer", surface by impact roller and vibration, surface by vibration, surface by equipment, surface levelled to not treated surface
Compartment's width [m]	From less than 100 to more than 1000
Compartments' wall construction method	From full height, "layer by layer" to "layer by layer" compacted
Particle size	Discards –150 or inter-burden as blasted
Slope angle [degree]	From less than 10 to natural angle
Height of stack [m]	From less than 5 to more than 30
Overburden sealing [m]	From 0 to more than 10
Overburden top level [m]	From less than 5 to more than 10
Sealing method	From slurry sealing placed in hydraulic way, slurry sealing placed mechanically, middling (power station coal) sealing, not sealed
If slurry, the period change [month]	From less than 3 to more than 9
Process moisture [%]	From less than 2 to more than 10

Table 4.2: Contribution Range of each Contributory Factor



Answer using "1" in boxes ☐

Assess according to time set in boxes

Spontaneous Combustion Database Risk Model

Range of Factors Contributing to Spontaneous Combustion

Material Risk Factors

Range / Contribution's Indicator

Indicator

Environmental Risk Factors

Mining Risk Factors

SA Adamski

Mining Engineer

Iscor Mining

Grootegeluk Coal Mine

Time after back filling of the Part of the Pit [years]: 5

Compartmet's exposure, before cover by new stacking level [months]: 21

Slope's exposure [weeks]: 8

Top surface's exposure [weeks]: 12

Spontaneous Combustion Risk within the Part of bac-filled Pit = 65

SLIGHT EVIDENCE OF RISK

Spontaneous Combustion Risk within filled Compartment = 95

SLIGHT EVIDENCE OF RISK

Spontaneous Combustion Risk within Stacking = -28

PROBABLY NOT !

Risk Assessment	-100	-70	-40	0	50	100	140	170	200
Interpretation	Definitely not	Almost certainly not	Probably not	Slight evidence		Probably yes	Almost certain	Definite	

Risk's Assessment for Back Filling of Pit of the Grootegeluk Coal Mine

Figure 4.2: Database Mathematical Risk Model

4.2.2 Use of the Database Mathematical Risk Model to determine Critical Time

The DMRM was intended to assess the risk of spontaneous combustion in the stacking area during backfilling of discard material into the pit. One of the critical contributing factors for spontaneous combustion is the time period that the slopes and the top of a specific layer are exposed to air (oxygen) before they are covered by the next layer of reactive waste material or a sealing layer. As an example of how the model can be used to assist engineers in the design of safe mining practices, the influence of backfilling rate (the time of exposure of material to air) on the spontaneous combustion risk was studied in several different ways. For this purpose, the influence of time on the risk was investigated for three different mixtures (GG3 and 4 running – highest reactivity, all plants running – most probable combination, and lowest reactivity while only GG1 runs). These mixtures were selected because they represent the widest range of reactivity. The environmental conditions were kept constant (at their medium level) in the model.

The results obtained are shown in ***Figure 4.3***, which illustrates that the risk of spontaneous combustion (SC) becomes critical after 13 weeks for GG3 and GG4/5 discards. For all plants running, the critical period is about 20 weeks.

The risk was also re-examined by assessing the influence of different environmental conditions for a constant type of discard material (all plants running) and it was found that the "safe" period is drastically reduced from 20 weeks in average conditions to 13 weeks in a hot, wet, windy summer.

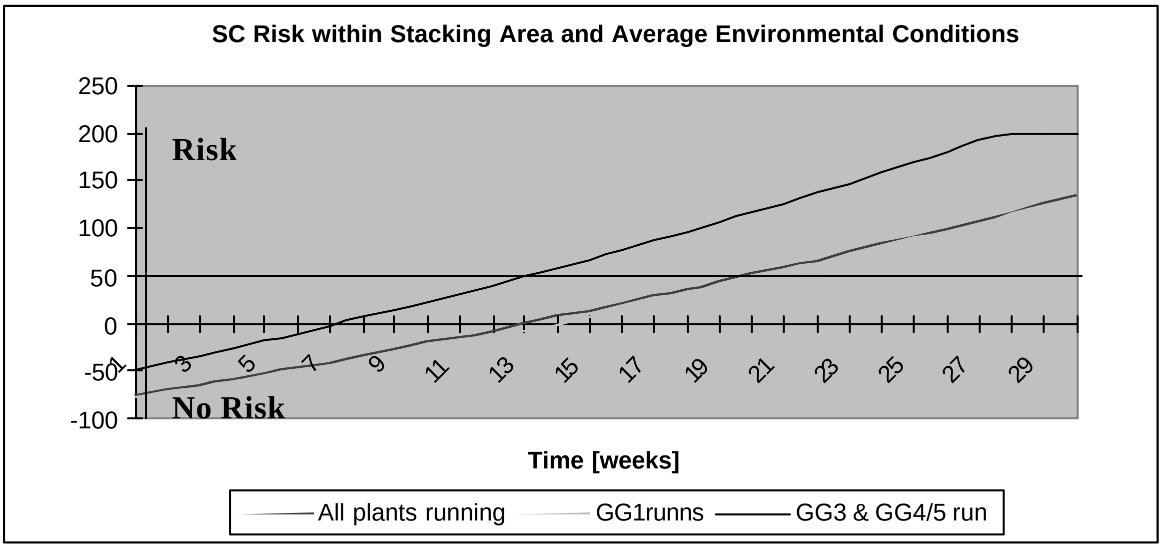


Figure 4.3: Risk of Spontaneous Combustion for Selected Waste Condition at the Average Annual -Environmental Conditions

It was also established from the model that the "safe period" is further reduced to eight weeks in a hot, wet, windy summer when GG1 and GG2 are standing (GG3 and GG4/5 running), i.e. the most reactive material. It was concluded that, to ensure that backfilling operations are safe at all times, the slopes must not be exposed for a period longer than eight weeks for any backfilling method.

The same study was done for surface exposure, i.e. the sides sealed and the top exposed. A three month period was concluded as the safe period.

The results were finally verified by testing them against confirmed findings from previous tests. Different elements will, however, influence the risk of spontaneous combustion within a waste stack, whether it is part of a backfilled or of a rehabilitated pit.

The continuous fluctuation in the ground water level in a pit is an example of an environmental factor that can cause the risk to fluctuate. Weather (rain, wind, humidity, heat, etc.) is another example of an environmental aspect that has a considerable impact on the fluctuation of contributing factors and their weight of contribution. It was evident that the risk of spontaneous combustion will have to be given greater emphasis and studied in more detail during the design of safe backfilling practices.

The design practices must have a sound resistance to the weather conditions and the negative contribution of the weather changes. The weather impact cannot be allowed to be immediate, it must be minimised and delayed and/or avoided as much as possible. The design practices must also additionally minimise the pollution problem associated with spontaneous combustion.

Specific risks that needed to be investigated during the large-scale test and the implementation phase included risk in the stacking area and risk in a backfilled compartment. The risk of spontaneous combustion within a part of a rehabilitated pit can only be investigated in future when all backfilling levels will be advanced.

The real behaviour of the waste material can only be found during a large-scale, backfilling test and this test is discussed in the next chapters.

4.3 Model of Backfilling Method

The existing database, the contributory model, recent test results and the sealing model, as well as the risk assessment results using the DMRM, gave sufficient confidence to proceed with a large-scale test of a backfilling method.

All previous experience indicated that only backfilling into pre-built and sealed compartments would be a solution for the Grootegeluk spontaneous combustion problem. To design a backfilling method, the most important aspects are the critical time (eight weeks for slopes and three months for surface areas) that reactive material can be exposed to air, and the sealing theory. As was shown previously, time is crucial in handling the spontaneous combustion problem. The critical time determines a stacking rate as well as the dimensions of backfilling compartments. To maintain the constant stacking rate, the compartments' widths must be fixed. Grootegeluk has constant geological conditions and the production budget, according to the long-term (40 years) planning, is relatively fixed. Therefore, the material distribution and dimensions of compartments can be planned as fixed parameters, see ***Table 4.3*** and ***Figure 4.4***. As shown in ***Figure 4.4***, the approximately 120 m deep pit will be backfilled to the natural ground level. The backfilling will be done using four levels. The first level will contain inter-burden material. The second and the third levels will contain plant discards, while the fourth sealing level will contain overburden material with a layer of about 1 m thick topsoil. The heights of the various levels are shown in ***Table 4.3***. These variable heights can change in future due to production changes, to allow a safe stacking rate to be maintained.

The compartments' widths should remain constant allowing for the maintenance of a safety-stacking rate. Only severe changes in the production levels for the pit will cause changes in the widths in order to maintain a safe stacking rate.

The intention of backfilling in the pit is not only to place discard material from the plants, but also to use inert material and pit waste that would otherwise need to be removed from the pit. The utilisation of this material in the backfilling operation is detailed in ***Table 4.3***, which also shows the percentage of each material that can be used in each level. A section through the backfilling operation is shown in ***Figure 4.4***.

This backfilling model will allow a new pit design. This model will have a huge influence on the main ramps and transport system of the Grootegeluk pit.

Stacking Level	Height [m]	Task	Material	Volume		Fixed Width and fixed Sectional area
				[Mm3/year]	[%]	
Level 1	32 First 5 years	Compartment walls	Bench 10	0.92	100	32x30
		Compartment filling	Bench 7a&8	3.46	100	32x100
	30 After 5 years	Compartment walls	Bench 10	0.92	100	30x30
		Compartment filling	Bench 7a&8	3.46	100	30x100
	3	Cover	Bench 1	0.6	10	3 m thick
Level 2	35	Compartment walls	Bench 1	1.37	23	35x(30+126)/2
		Compartment filling	Plant Discards	4.33	50	35x(200+296)/2
	3	Cover	Bench 1	0.6	10	3 m thick
Level 3	35	Compartment walls	Bench 1	1.37	23	35x(30+126)/2
		Compartment filling	Plant Discards	4.33	50	35x(200+296)/2
Level 4	10	Cover	Bench 1	1.89	32	About 9 m thick
		Rehabilitation	Top soil	0.10	2	About 1 m thick

Table 4.3: Backfilling Programme

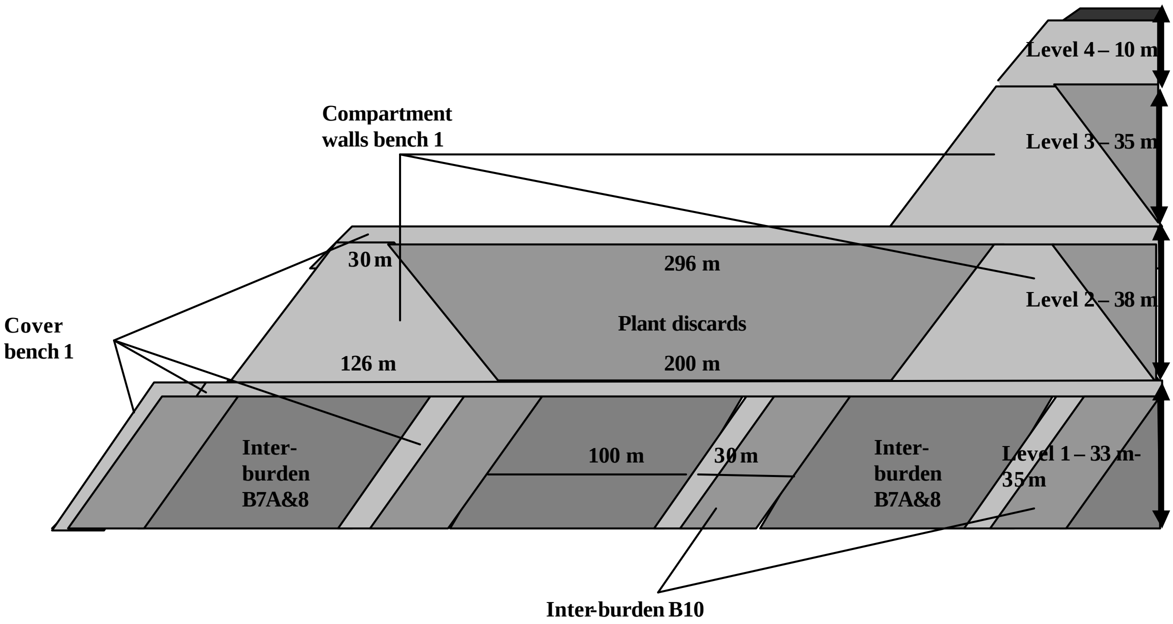


Figure 4.4: Backfilling Method (West-East Section)

5 FULL-SCALE TEST

The complexity, as defined in Chapter 4, was to test the sealing theory and the backfilling model during a large-scale test to decide on the final backfilling method. The decision was taken in May 2000 by Grootegeluk management to carry out the large-scale test to determine the final backfilling method.

5.1 Need for comparing Inter-burden and Plant Discards

It was crucial during the full-scale, backfilling test to compare the behaviour of plant discards with inter-burden containing bench 7B material and with inter-burden excluding bench 7B material. The

]

decision was taken that the full-scale tests would be carried out according to the backfilling model (***see Figure 4.4***). This was done in order to finalize the decision on the backfilling method.

The so-called inter-burden benches (benches 7A, 7B and 8) were blasted together in the past as one bench. The difference between the material characteristics of the different benches were not taken into account at that stage, and the method used was the most economically viable option, even though it was not environmentally friendly in terms of spontaneous combustion management.

5.1.1 Large-scale Test Planning

In order to draw the correct conclusion, the plant discards and the inter-burden containing bench 7B material had to be handled under the same backfilling conditions as the inter-burden material not containing bench 7B, before a final decision could be made on a safe backfilling method.

The material that was planned to be backfilled within Level 1 (see ***Figure 4.4***) does not contain bench 7B.

The volume of the first-year compartment of the large-scale test was planned therefore to accommodate the annual production of the inter-burden benches 7A and 8, according to Grootegeluk's production budget. Due to the very low reactivity of benches 7A and 8, the risk of spontaneous combustion was very low, as defined in Chapter 4. Furthermore, the low risk was reduced even further by the proposed preventative method of backfilling into sealed compartments.

The eastern pit boundary is not parallel to the working faces, which meant that the backfilling that had to be done would not be symmetrical with regard to the working faces. Provision had to be made for an in pit water storage dam (***Figure 5.1***). Therefore, the backfilling needed to be done in a triangular shape, between the water dam and bench 11's advance (bottom bench), which meant that a constant stacking rate could not be achieved, and that material would then be exposed to oxygen for longer than the critical time.

Consequently, the first-year large-scale test compartment had to be divided into three sub-levels, 11 m each in height, to maintain the critical stacking tempo. The three sub-levels were planned to accommodate the annual-budgeted volume of benches 7A and 8. The lower height allowed the stacking rate to be maintained according to the requirements of the critical time, as defined in Chapter 4. The three sub-levels allowed for good compaction due to the presence of operating equipment such as trucks and assisted in decreasing the segregation effect that occurs on the slopes where the material has been dumped due to the lower height. Therefore, a very low risk of spontaneous combustion was found for the first-year compartment of the large-scale test.

A comparison of the behaviour of plant discards and inter-burden containing bench 7B was essential. For economic reasons, the possibility still exists to reconsider the mining of benches 7A, 7B and 8 together as one unit, because the selective mining of coal from bench 7B is very costly. It was decided to simulate this condition in a compartment containing a minimum of 30 000 t. A compartment smaller than this could not represent the real thermo-dynamic condition. The decision was made that two compartments, which could accommodate at least 55 000 t each, would be designed to conduct a large-scale test for comparison purposes. To obtain the inter-burden material from benches 7A, 7B and 8, the compartment was allocated in the pit within the south-east corner of the Grootegeluk pit, where the geometry of the pit required one block of the benches 7A, 7B and 8 to be blasted together. This block contained about 200 000 t and it was decided to build the large-scale test compartment with benches 7A, 7B and 8 according to this tonnage.

It was decided that, after completion of the third sub-level of the first-year compartment containing benches 7A and 8 inter-burdens, when the full height of 33 m was reached, two compartments of the plant discards and inter-burden containing benches 7A, 7B and 8, respectively, should be built. The two compartments were built next to the north-west corner of this compartment, see ***Figure 5.2***. The one compartment was filled with plant discards and the other compartment with Bench 7A, 7B and 8 inter-burdens which were blasted as one bench. Building three compartments of different reactivity (low reactive inter-burden of benches 7A and 8, more reactive inter-burden of benches 7A, 7B and 8 and plant discards), meant that the sealing theory discussed in Chapter 4 could be tested in real backfilling conditions. This opportunity made it possible to establish the real contribution of the 3 m thick layer of overburden material used for sealing compartments containing different materials in terms of reactivity towards temperature. This decision was classified as a high risk by the management team of Grootegeluk who considered it thoroughly. Both types of waste material, plant discards and the inter-burden of benches 7A, 7B and 8, had a high spontaneous combustion risk according to the DMRM.

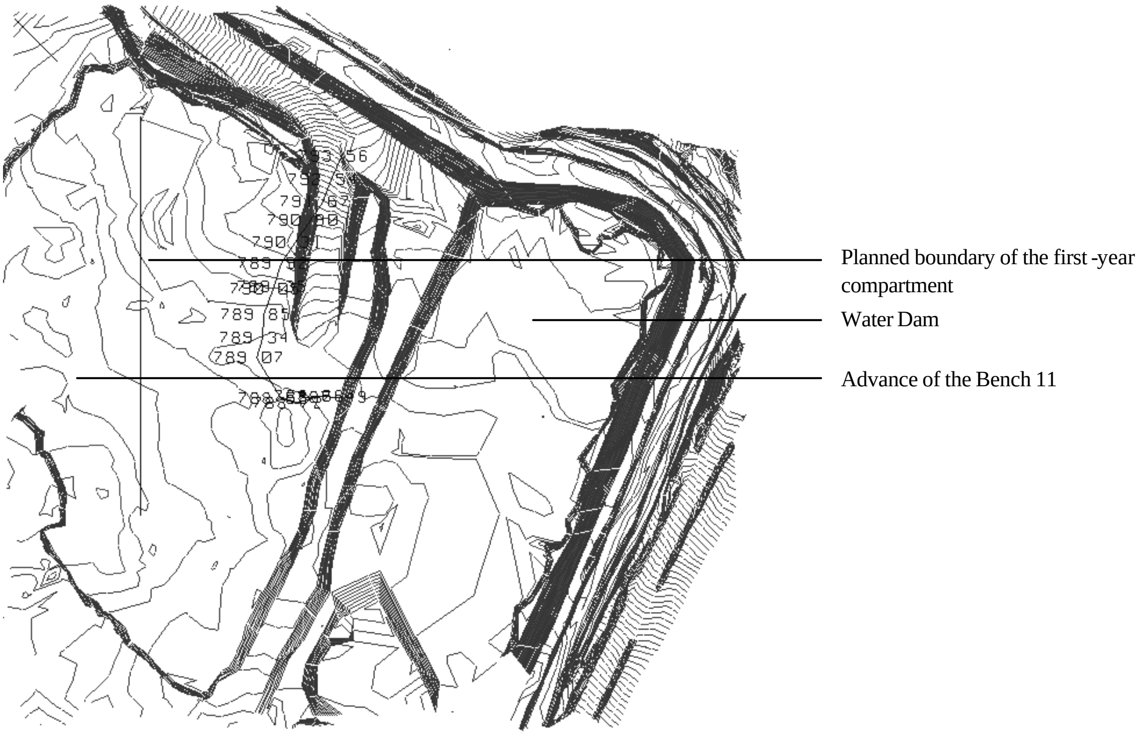
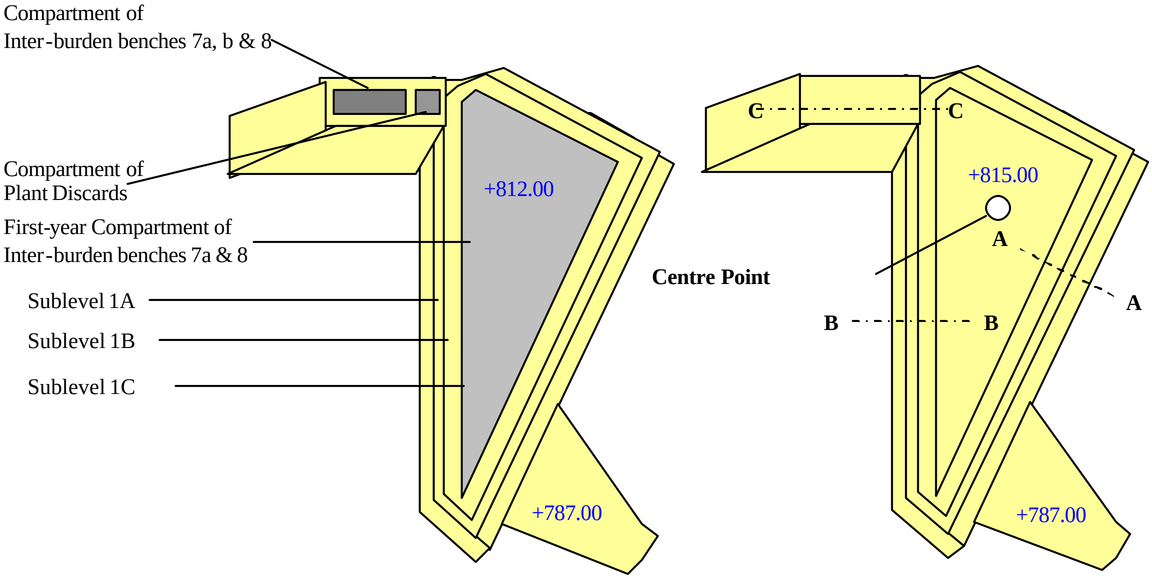


Figure 5.1: Bottom of the Pit, May 2000



Before Sealing

After Sealing

Figure 5.2: Large-scale Test Planning

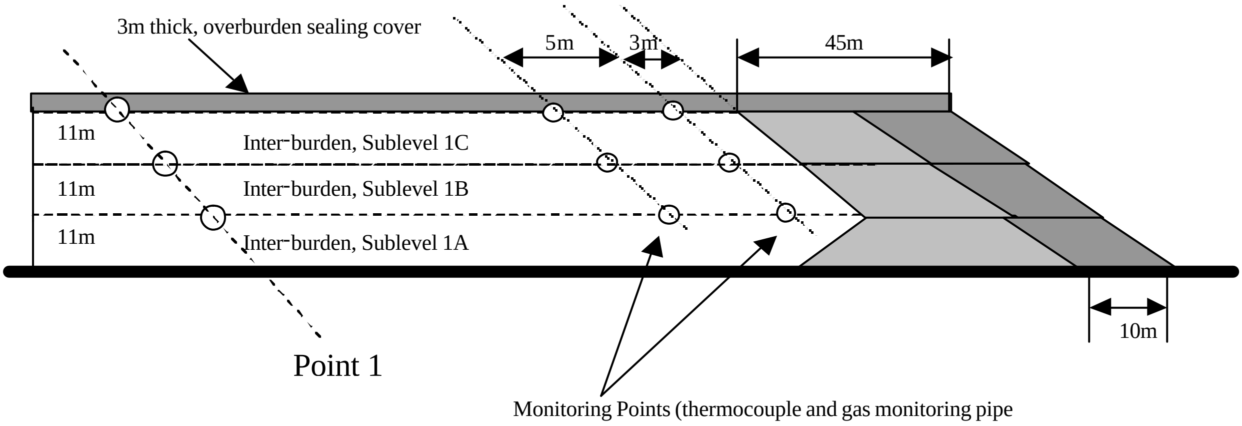
5.1.2 Monitoring System

In line with the saying: “In order to manage, you need to measure”, it is necessary to monitor temperature and gases within all compartments. A temperature and gas monitoring system was installed as shown in ***Figure 5.2*** and ***Figure 5.3***. Thermocouples that are capable of measuring up to 1200 °C were installed on the sides of each level as well as in the centre.

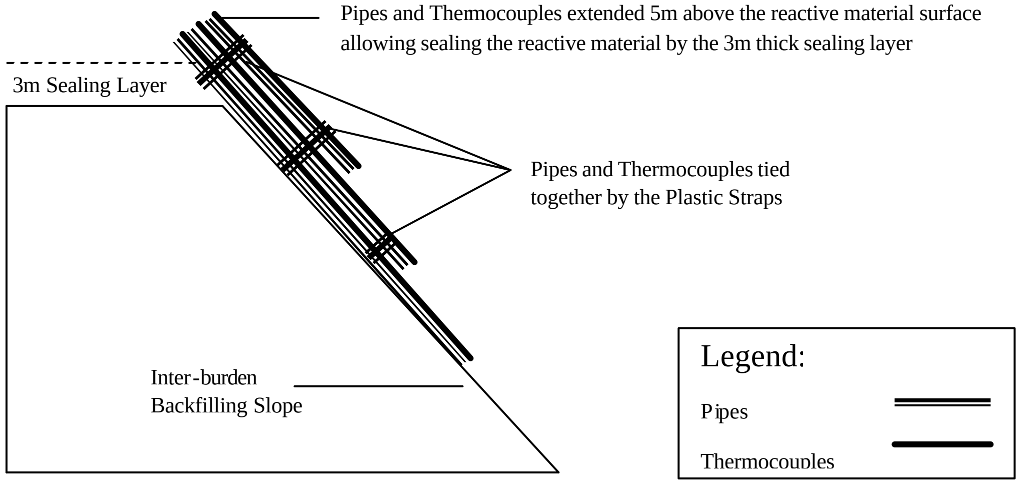
Monitoring system – Section A-A (see *Figure 5.2*)

Section B-B is a mirror image of A-A

The sealing wall is reduced to 30m, including 5m overburden sealing at the West wall Section B-B



Point 1 - Installation



Monitoring system – Section C-C (see *Figure 5.2*)

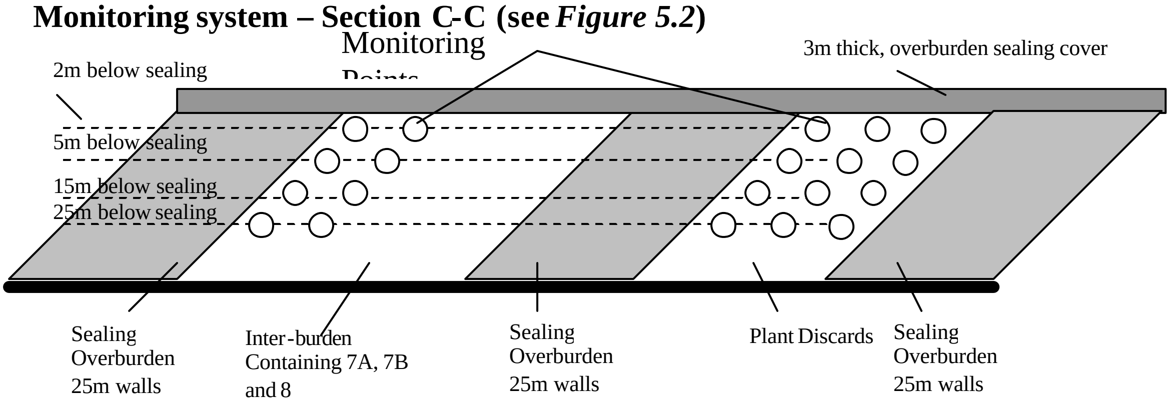


Figure 5.3: Monitoring System

Section A-A and B-B (***Figure 5.3***) show the system within the sub-levels about 3 m and 8 m from the sealing walls.

Section C-C (***Figure 5.3***) shows three monitoring points on the same level installed within the plant discards compartment. These three points were installed on all four levels. Two monitoring points on four different levels were installed within the compartment containing material from bench 7A, 7B and 8. The reason for more monitoring points within the plant discards was due to their high reactivity and on request from Grootegeluk management. It was essential to have a very good early-warning system, allowing quick action in case of an unexpected temperature increase.

At point 1 (***Figure 5.3***), a monitoring system was installed within all three sub-levels in order to measure the centre of the first-year compartment. Professor Phillips requested this installation.

It was decided to monitor temperature and to sample gas from these points monthly to get an indication of the stability of the heap. As soon as the heap started to heat up, CH_4, CO and CO_2 levels would increase. Therefore, it was decided to monitor and sample these gases, as well as oxygen content. In the case of an increase in risk, the frequency of monitoring would be changed to weekly. The results are discussed in the next section.

Temperature and gas monitoring were very important to determine how the stockpiled material was behaving. The 3 m thick layer, which should be sufficient according to he sealing theory, based on the column test results, commenced testing. If any instability were be detected, a thicker sealing layer would have to be used.

5.2 Construction of Large-scale Test Compartments

The decision was to commence the large-scale backfilling test in May 2000. The first material placement took place on 20 May 2000. The significant responsibility of the pit teams was to dump and place material selectively, according to the demarcated compartments and the sealing walls. Training of all supervisors was done, including all truck operators, with regard to the main assumptions of the sealing theory and compartments.

5.2.1 First-year compartment (benches 7A & 8)

The area for the first-year compartment was allocated, allowing a height of 33 m (3 x 11 m for each sub-level) to be accommodated (see ***Figure 5.4***).

West, sealing-wall, 30 m (Including 5 m thick layer of overburden)

Construction Progress of the Sub-level 1A

East, sealing-wall, 45 m (Including 10 m thick layer of overburden)

Figure 5.4: Planning of First-year Compartment

The eastern sealing wall was constructed first, using sandstone from bench 10 (45 m thick), which followed the boundary of the dam used for the water recycling project. After the 11 m high wall was completed, the reactive inter-burden material from benches 7A and 8 was backfilled from the north-east corner of the north ramp and the abovementioned wall, see ***Figure 5.4***. The progress of the construction of the first-year compartment is illustrated pictorially in ***Figures 5.5, 5.6, 5.7 and 5.8***.

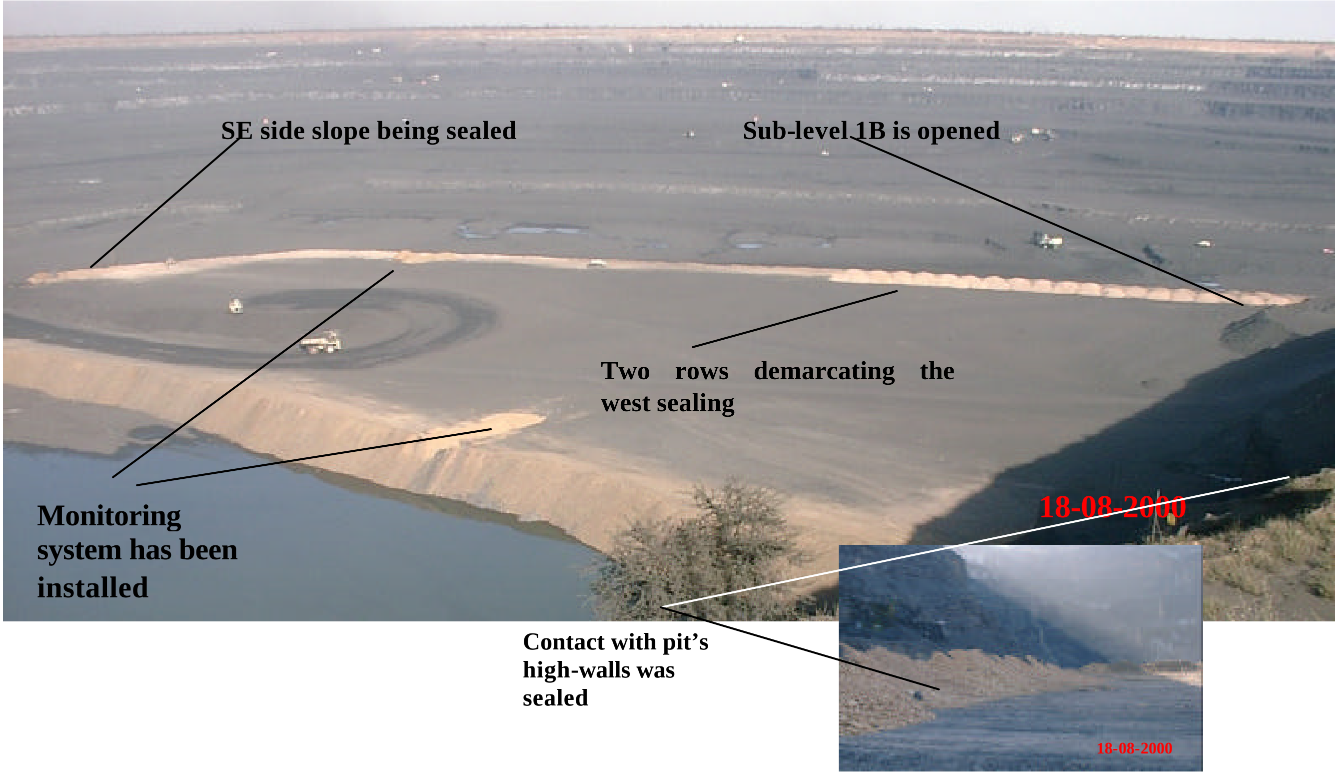


Figure 5.5: First-year Compartment, Sub-level 1A Completed

The specific material-placement practice was important as materials could not be mixed. Two lines of off-loaded overburden material demarcated the sealing walls. This line indicated the boundary of the reactive inter-burden material from benches 7A and 8, see ***Figure 5.5.*** To avoid a risk of transferring spontaneous combustion to the pit's high-walls, the contact area was isolated by inert material from overburden or bench 10–sandstone, see ***Figure 5.5***. The installation of thermocouples and gas monitoring pipes is shown in ***Figures 5.5 and 5.6***. While the construction sub-level was advanced, the new sub-level was open. This practice allowed the continuation of backfilling at the required constant dumping rate. Due to subsidence, self-compaction and/or rain, cracks along the walls occurred. The sealed walls were maintained by grading and/or adding new layers of overburden material. This was an important action which had to be done within the time period of two to three months after sealing. Furthermore, after each rainfall all the walls were inspected for cracks and damage. A standard working practice was established regulating the intervals of inspections in this regard. It was decided to inspect all slopes of the sealing walls monthly.

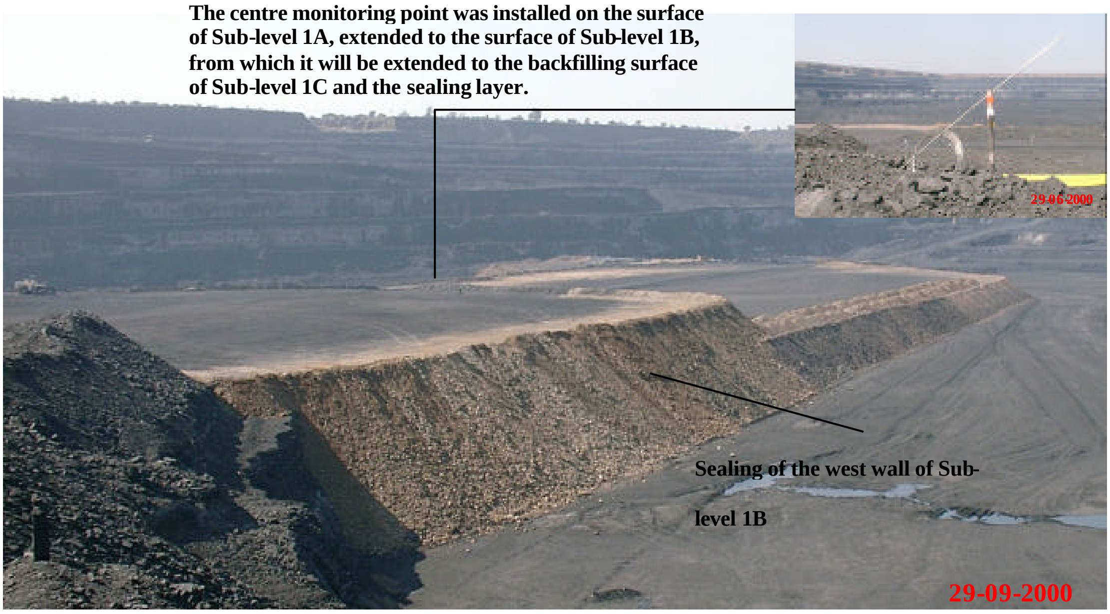


Figure 5.6: First-year Compartment, Construction of Sub-level 1B

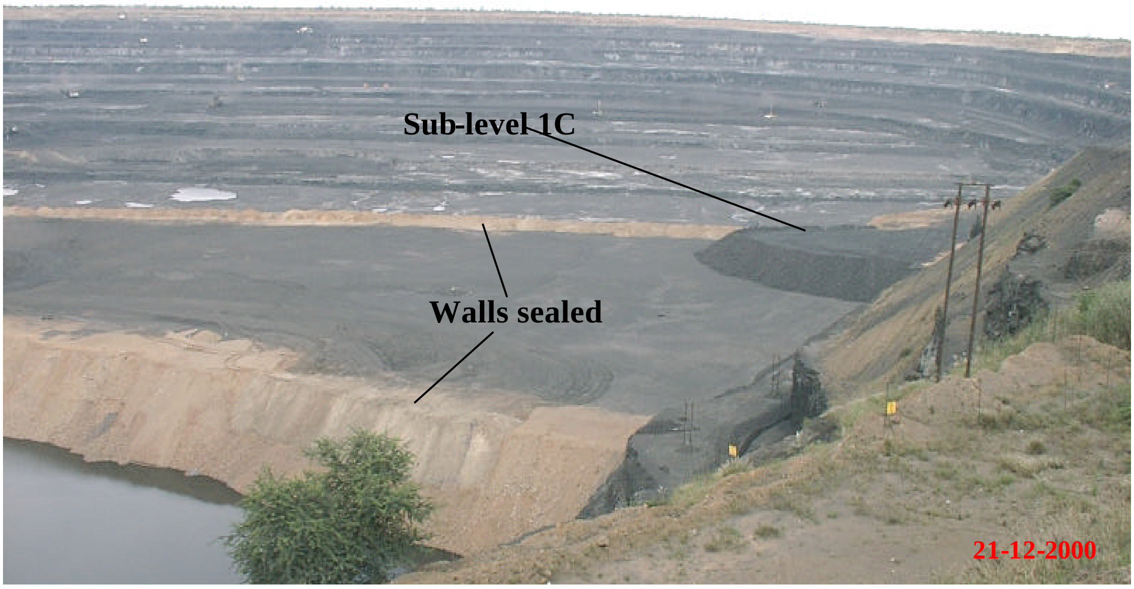


Figure 5.7: First-year Compartment, Construction of Sub-level 1C

After completion of the third sub-level of the first-year compartment of the large-scale test, the surface sealing began. The process of surface sealing is illustrated in ***Figure 5.8***. The overburden material was dumped within the area and then levelled and compacted by the weight of the trucks that delivered the new material for sealing purposes.


29-06-2001

Figure 5.8: First-year Compartment, Surface-sealing of Sub-level 1C

The sealing theory was applied and monitoring commenced. Given the stable conditions within the sealed first-year compartment of the large-scale test, the very reliable monitoring system and the high quality of backfilling activities, the Grootegeluk management decided to continue backfilling inter-burden reactive material from benches 7A & 8 into the working pit according to the backfilling model of this thesis. It was decided to build the second-year compartment with material from benches 7A and 8 after completion of the large-scale test compartments containing plant discards and the inter-burden of benches 7A, B and 8.

5.2.2 Plant Discards and Inter-burden Benches 7A, 7B & 8 Compartments

During April and May 2001, the third sub-level of the first-year compartment was developed, see ***Figure 5.9***.

The construction and installation of the monitoring system was implemented according to plan, except for one point within the compartment of benches 7A, B and 8, which needed to be removed due to convection of air that occurred after the installation. The ingress of air was extremely dangerous and could cause spontaneous combustion around this monitoring point. This situation had an enormous risk for the rest of the mining activities, especially because it was inside of the operating pit.

This allowed the building of a plant discards compartment. After construction of the plant discards compartment, the compartment for inter-burden from benches 7A, B and 8 was built. A series of pictures (***Figures 5.9 and 5.10***) illustrate the construction process.

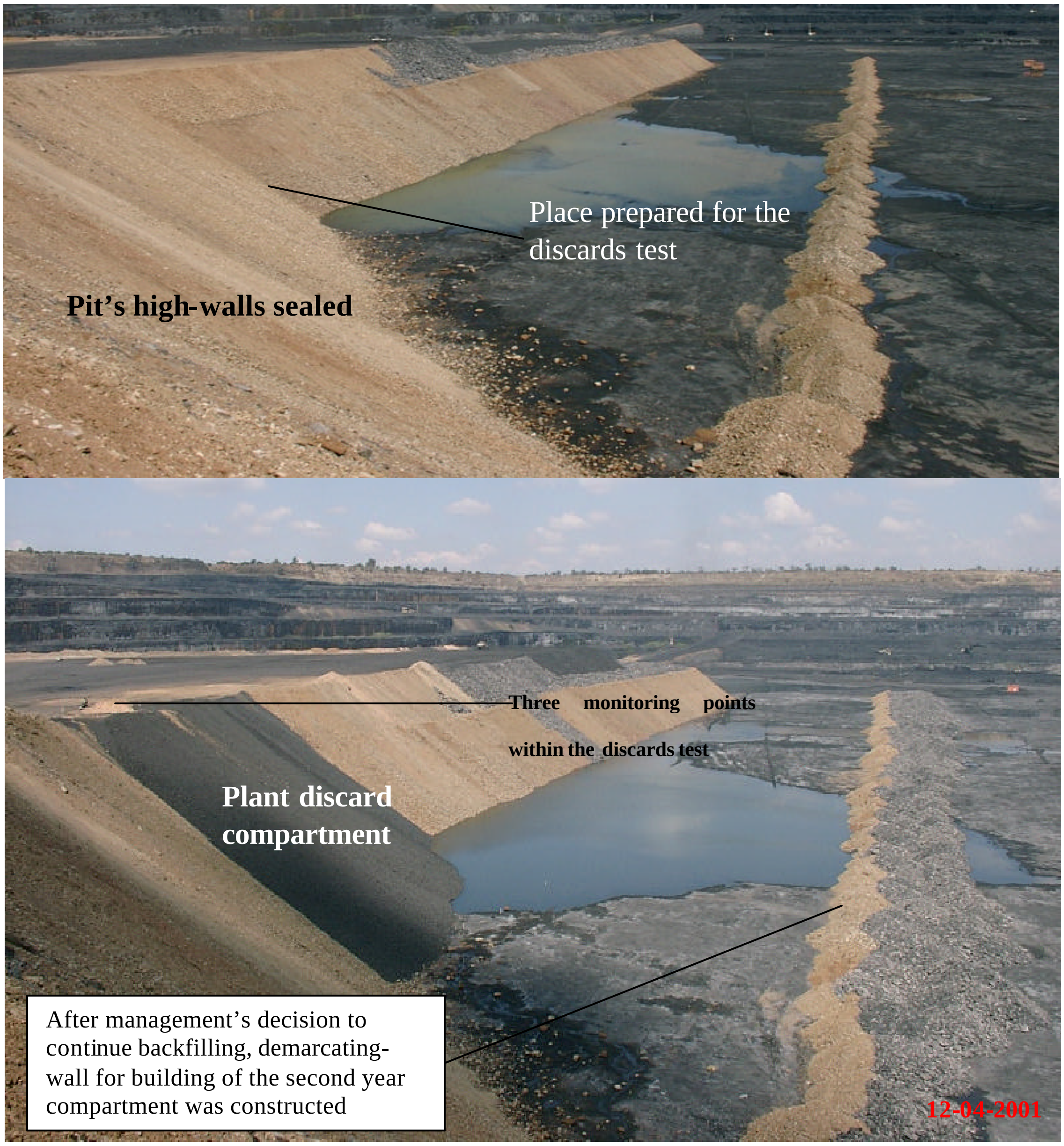


Figure 5.9: Plant Discards Compartment

Although the high-wall was sealed as illustrated in ***Figure 5.9***, a risk existed that spontaneous combustion could start at the monitoring point and could be transferred to the pit's hauling roads. The risk assessment led to the immediate decision to remove the monitoring point from the area that was affected by convection. This monitoring point is visible before removal in ***Figure 5.10***.

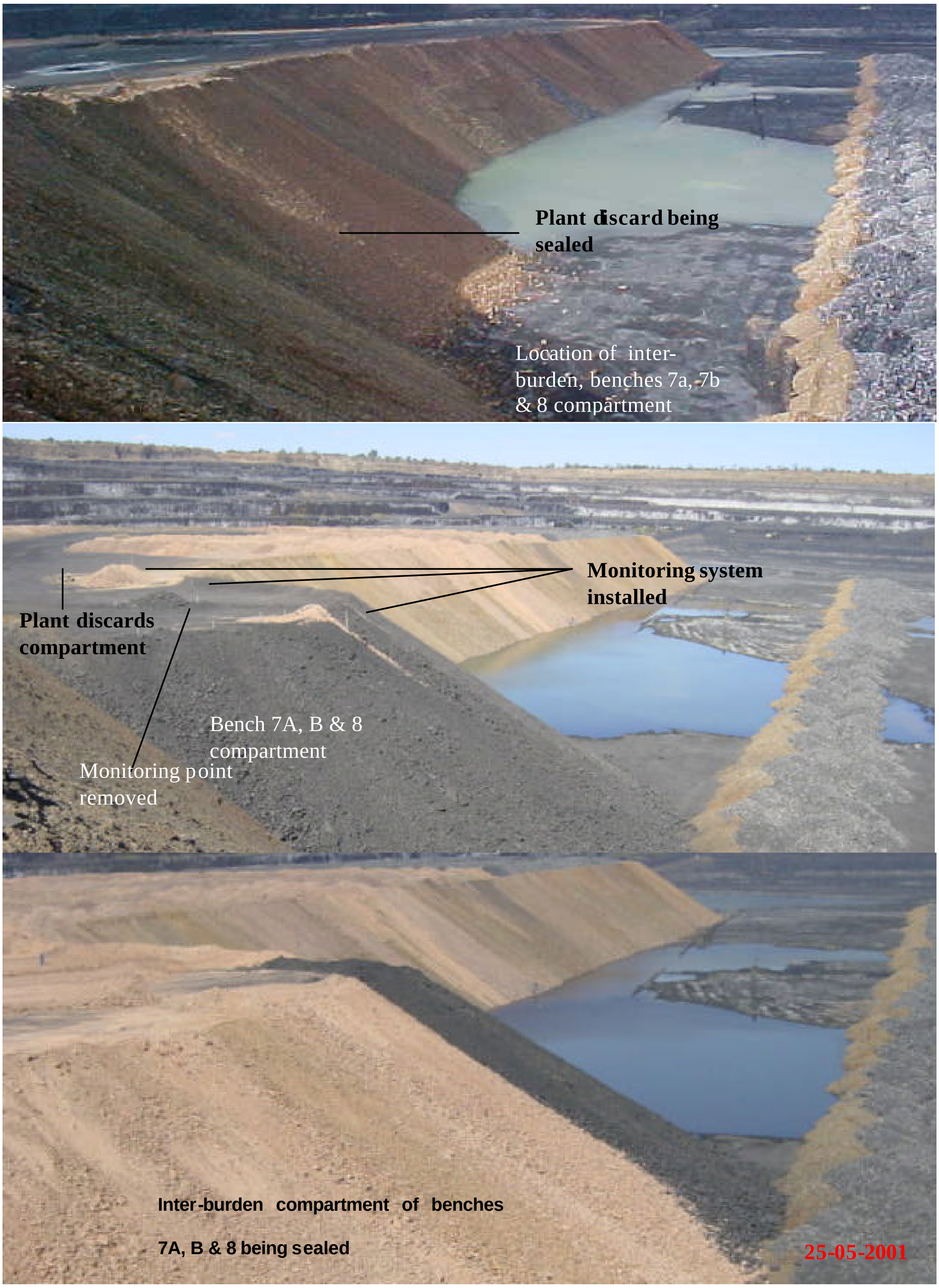


Figure 5.10: Inter-burden, Benches 7A, 7B and 8, Compartment

5.3 Design of Backfilling Method

The very stable conditions within all three compartments of the large-scale test and the high quality of work during the compartments' construction led to the Grootegeluk management deciding on building the second-year compartment of benches 7A and 8 and to continue the backfilling process. It was important to design the backfilling method specifically for the Grootegeluk pit.

5.3.1 Description of Pit

Layout of the Pit

The Grootegeluk pit is divided into 11 working benches (See ***Figure 5.11***).

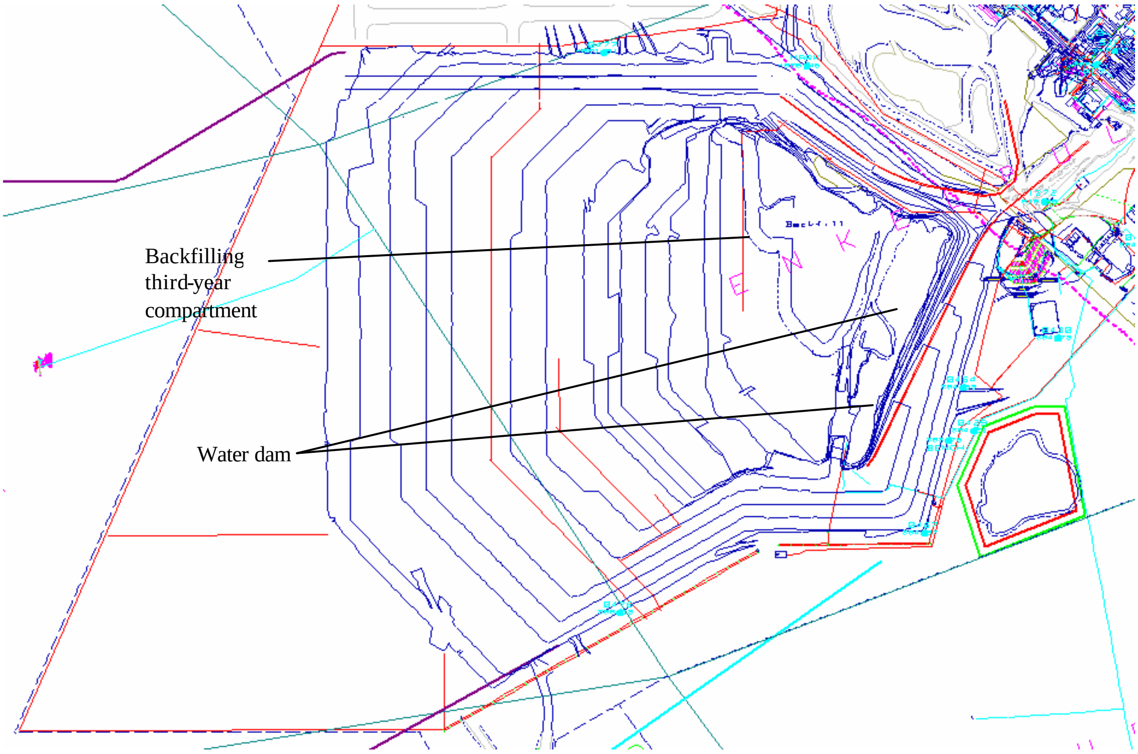


Figure 5.11: Grootegeluk's Pit, May 2002

Benches 1, 7 and 9 are sub-divided into 1A, 1B, 7A, 7B and 9A and 9B. This gives a total of 14 benches. The dimensions of the pit at the ground level are: 2 000 m from north to south and 2 500 m from east to west. The eastern part of the pit's bottom is used for a water dam. The water dam is utilized for an industrial-water recycling system, accommodating water from the plant operations. The northern part of the dam, the sediment dam, is employed to clarify the plant's water. The southern part of the dam contains clean water which is recycled back to Grootegeluk's plants. Next to the water dam, towards the west, is the backfilling dump (see ***Figure 5.11***). The third-year compartment is progressing, with the sealing layer visible in the back of the compartment's advance. Mining equipment travelling on the backfilling compartments led to compaction of the sealing layer.

Mining Equipment

Three Tamrock D25KS drill rigs are used to drill 172 mm diameter blast holes. A total of 504 000 m are drilled annually. A contractor is responsible for the blasting operation.

The blasted material is loaded, respectively, by five 19 m^3 hydraulic rope shovels, four 16 – 20 m^3 hydraulic shovels and one mobile 994 Caterpillar face shovel. The rope shovels are used on the five upper benches and the hydraulic shovels for the selective mining of benches 6 to 11. The hydraulic shovels are capable of mining the geological contacts very accurately and, with their high breakout forces, are ideally suited to the mining requirements of the Middle Ecca benches.

The fleet of haul trucks consists of:
14 X 200 t Komatsu 730E trucks
6 X 180 t Titan 2200 trucks
4 X 255 t Euclid R280 trucks

5.3.2 Description of Backfilling Method

Backfilling Theory
Backfilling into pre-built and sealed compartments with a fixed width to allow constant, safe stacking (dumping) rates is found to be a safe method (in terms of combustion).

The most important suppositions of the theory are:

a) ***Filling material into pre-built compartments*** to isolate reactive material within slopes, where the risk is the highest and to control eventual combustion within one compartment
b) ***Building compartments with a fixed width*** to maintain a constant stacking rate, determined by the risk model as the safe rate and to maintain a constant ratio between different types of the waste materials
c) ***Sealing of the compartments*** to isolate reactive material between levels and compartments and to handle combustion within one compartment, in case of combustion
d) ***Isolating reactive waste from the pit's high-walls by a layer of benches of 10 or 1 material*** to prevent transfer of combustion into the high-walls, in case of combustion (benches 10 and 1 contain inert materials, which have no risk of spontaneous combustion)

As discussed previously, using the DMRM different conditions were simulated for backfilling into sealed compartments. Critical times (understood as safe periods for slope and surface exposure for the most dangerous conditions during hot and wet summer months, and the most reactive mixture of waste material) were identified and built into the most important operational standards. The most critical conditions allowed the application of a safety factor for backfilling activities.

According to this theory, the following application must be followed:
Slopes within the stacking (dumping) area cannot be exposed for longer than eight weeks. ***The eight-week period represents the critical time for slope exposure.***
The surface of any stacking level cannot be exposed for longer than three months.
The three-month period represents the critical time for surface exposure.
Stacking dimensions and stacking rate must adhere to the above.

Scheduling of the Backfilling Operation
Scheduling of the backfilling process is shown ***in Table 5.1.***

Stacking Level	Height [m]	Task	Material	Volume		Dimensions	Commence Date
				[Mm3/year]	[%]		
Level 1	32 First 5 years	Compartment walls	Bench 10	0.92	100	32x30	May 20, 2000
		Compartment filling	Bench 7a&8	3.46	100	32x100	May 20, 2000
	30 After 5 years	Compartment walls	Bench 10	0.92	100	30x30	2004
		Compartment filling	Bench 7a&8	3.46	100	30x100	2004
	3	Cover	Bench 1	0.6	10	3 m thick	On going
Level 2	35	Compartment walls	Bench 1	1.37	23	35x(30+126)/2	2004
		Compartment filling	Plant Discards	4.33	50	35x(200+296)/2	2008
	3	Cover	Bench 1	0.6	10	3 m thick	On going
Level 3	35	Compartment walls	Bench 1	1.37	23	35x(30+126)/2	2010
		Compartment filling	Plant Discards	4.33	50	35x(200+296)/2	2013
Level 4	10	Cover	Bench 1	1.89	32	About 9 m thick	2013
		Rehabilitation	Top soil	0.10	2	About 1 m thick	2013

Table 5.1: Backfilling Timetable

It was important to include a safety factor for slope stability in the scheduling. The total slope angle of the backfilled pit (all four levels) cannot be more than 22^0. This angle was calculated for Grootegeluk's dumps in 1980. Due to the water dam, the eastern slope of the backfill could not be supported by the high-wall of the boundary of the pit. Therefore, both sides of the backfill had to uphold this safety angle.

The scheduling was done according to the safety factor of slopes discussed above and a materials ratio. Opening of discard backfilling levels can be ignored due to the necessity of completing the current stacking dumps of the "U and L" stacking systems.

Even though the geological conditions of Grootegeluk mine will be relatively constant for the next 40 years, it is very important to understand that the budget of Grootegeluk Coal Mine can change over time. Therefore, reconciliation of the scheduling (***Table 5.1***) and the long-term planning, which is discussed in the next section, must be adjusted in future by the short-term planning.

Planning of Backfilling

In the long-term planning there is a correlation between the production advance and the Level 1 backfilling advance (see ***Figure 5.12, 5.13 and 5.14***). It is important to maintain a safe distance between both advances for the safe movement of mining equipment and the power line on bench 11 (bottom of the pit). More details of the 15-year planning are presented in ***Appendix E.***

Currently, the short-term planning for backfilling is influenced by additional projects:

Project 1

Grootegeluk Mine is considering exploitation of bench 13, 12 m below the current pit bottom. Extraction of this seam is considered in two ways: open cut mining and an underground method. Spontaneous combustion will be a major consideration in deciding on the mining method.

Project 2

Grootegeluk Mine is taking into account extraction of coal from benches 11 and 9 around available high-walls, using the high-wall mining method, which is popular throughout the world.

Project 3

Due to the rain disaster in April and May 2002 (145 mm on16 April and 55 mm on 30 May), Grootegeluk Mine is in need of an additional sump between the backfilling and exploitation advances. This sump must be moved annually and has direct correlation to the opening of bench 13.

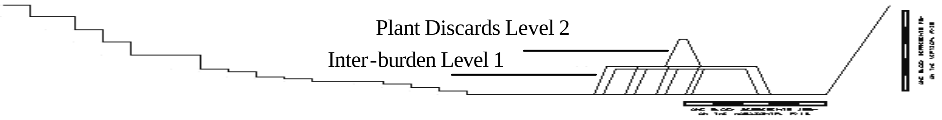


Figure 5.12: Backfilling Advance, 2005

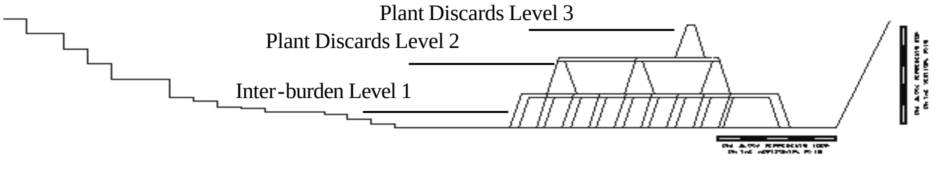


Figure 5.13: Backfilling Advance, 2010

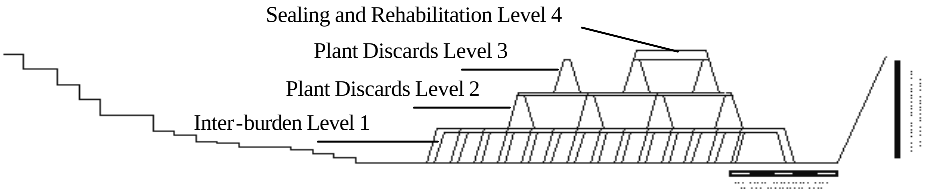


Figure 5.14: Backfilling Advance, 2015

5.3.3 Backfilling Practice

The Safety and Environmental Department of Grootegeluk Mine included the backfilling method in the Waste Handling Code of Practice, accepted by ISO 1400 and DME.

This achievement was possible due to very stable conditions within all large-scale test compartments and the extremely high quality of the backfilling process, as well as the high standard of work. All employees involved in this process have a basic understanding of the standards and are extremely conscientious in the selective dumping of materials. The stable conditions represented by the results of temperature and gas monitoring are discussed in the next section.

Continuation of Backfilling

During construction of the large-scale test compartments, it was experienced that, during thunder storms, the sealing layer of weathered overburden was washed out in some places at the slopes. Placement of an overburden sealing layer on top of the sandstone layer covering the reactive material did not secure good slope stability.

Before construction of the second-year compartment containing inter-burden from benches 7A and 8 (level 1), a decision was made to change the sealing sequence. The 5 m thick weathered overburden sealing layer was to be placed directly onto the slopes of the reactive material at the boundaries of the compartments and, in order to stabilize the slopes, a 25 m thick layer of sandstone was to be placed on the 5 m thick layer of overburden sealing, see ***Figure 5.15***.

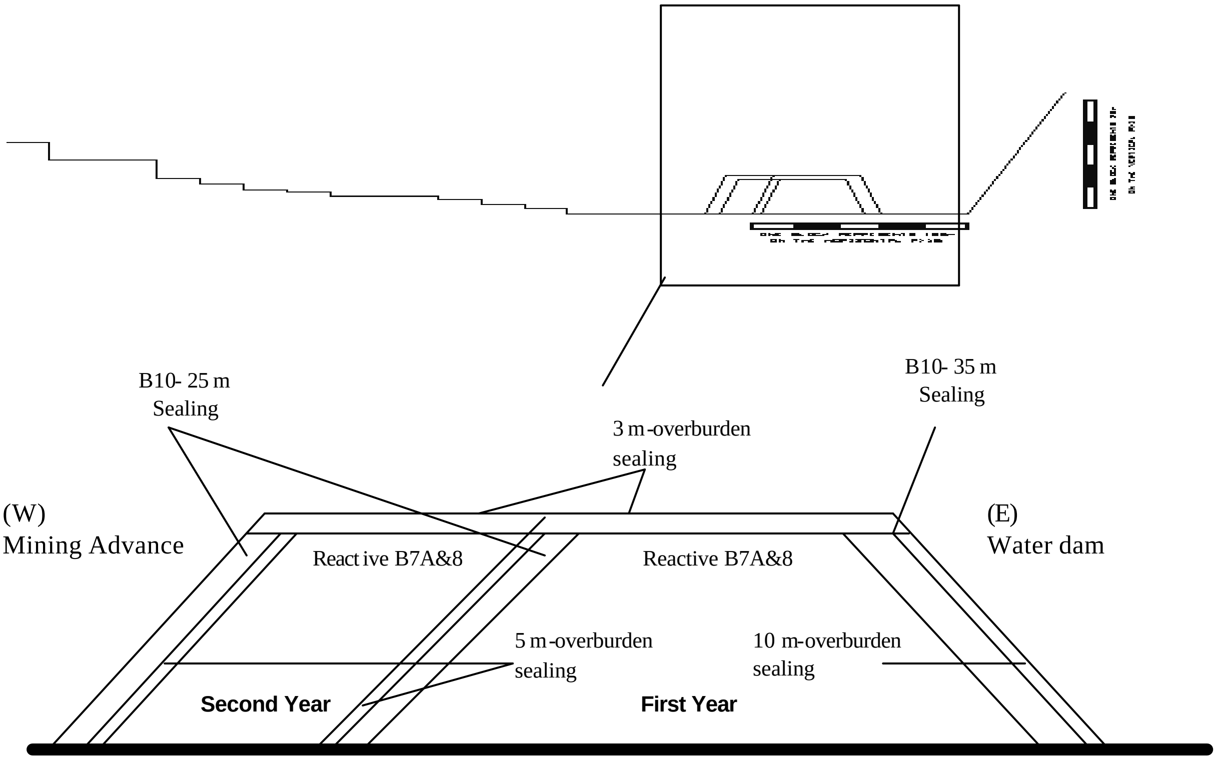


Figure 5.15: Second-year Compartment of Inter-burden Benches 7A & 8

The reason for changing the sealing sequence was to make certain that the slopes were more stable with the 25 m of sandstone on the side. The sandstone will not be eroded by water and will additionally compact the 5 m-overburden sealing layer, which will effectively decrease the permeability of the sealing layer.
After completing the plant discard and inter-burden (benches 7A, B & 8) compartments for the large-scale test, the second-year compartment was sealed according to this new sealing sequence.

Figure 5.16 illustrates the sealing sequence and the isolation of high-walls from the reactive material by the placement of a collar of sandstone or overburden material.

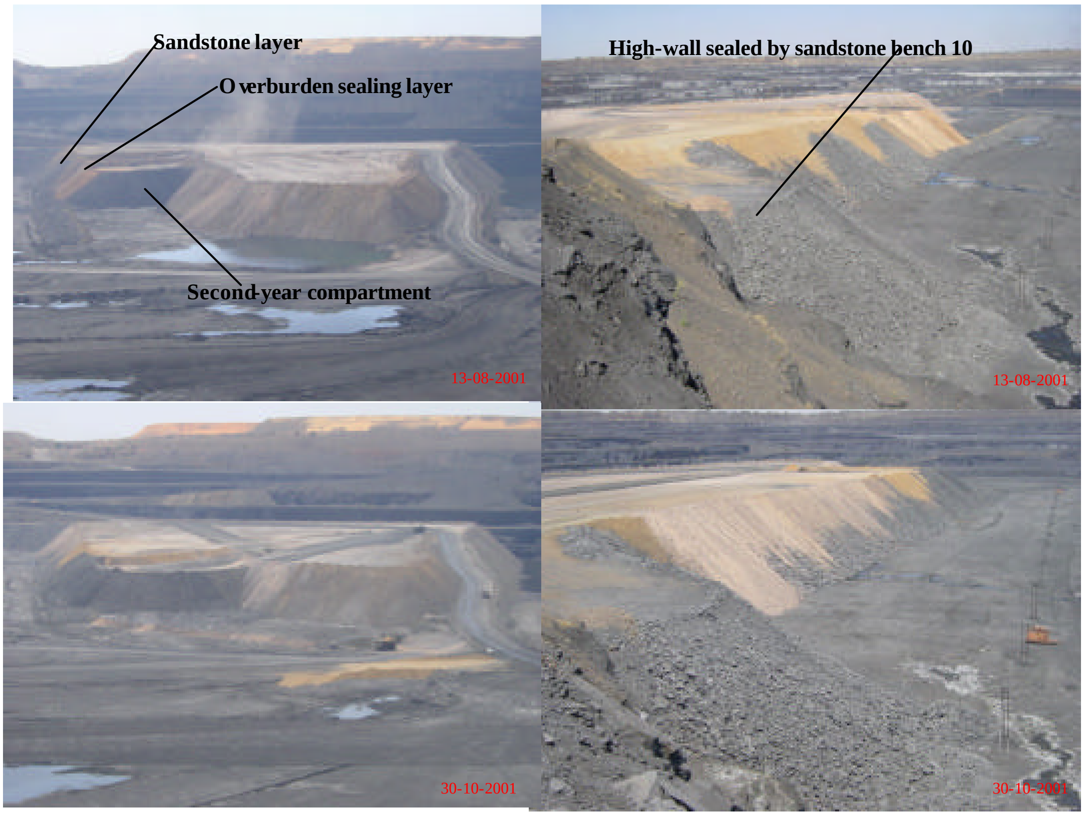


Figure 5.16: Second-year Compartment

Currently, construction of the fourth-year compartment is in process, with the third-year compartment having been completed in November 2002 (see the third-year compartment ***Figure 5.17***).

Figure 5.17: Third-year Compartment

After completion of the third-year compartment, the southern part of the pit was to be backfilled (see ***Figure 5.18***). The backfilling of this small compartment, named the fourth-year compartment, was to take place on three sub-levels to maintain a safe backfilling rate, adequate for the critical time of exposure.

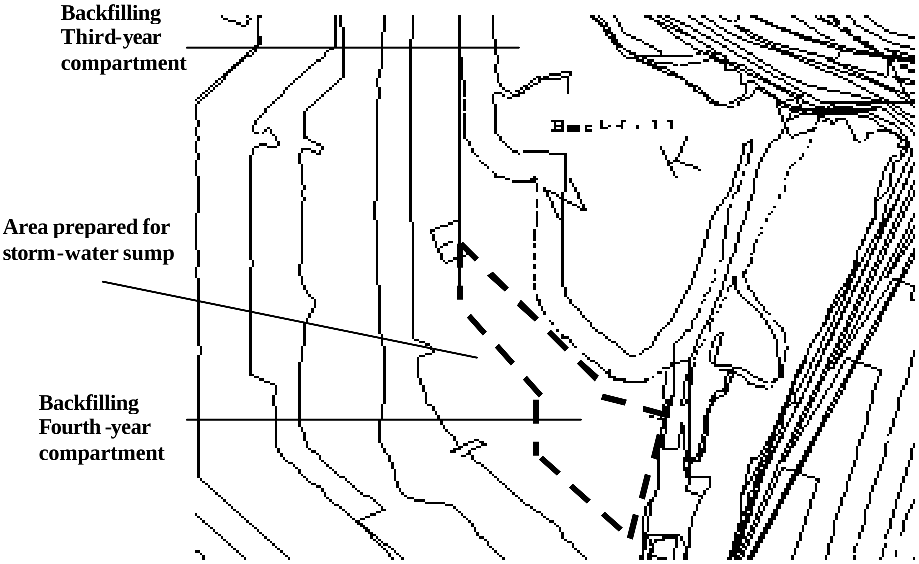


Figure 5.18: Provision for Next Compartment

This compartment will only contain the half-year budget tonnages for inner-burden production from benches 7A and 8. The reason for such a decision was the shape and dimensions of this fourth-year compartment, see ***Figure 5.18***. Construction of the fourth-year compartment is illustrated in ***Figure 5.19***. The storm water sump is visible between the backfilling and bench 11 advances. Construction of the storm water sump allowed exploration of bench 13 and further study on eventual exploitation of the bench.

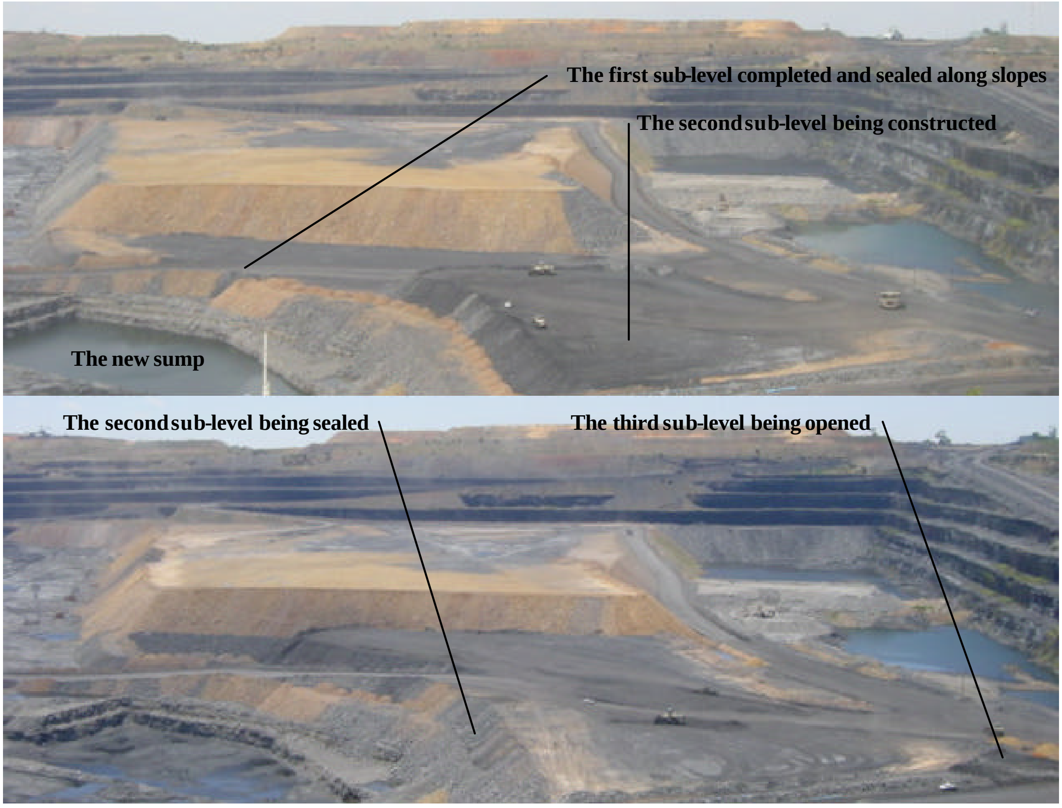


Figure 5.19: Fourth-year Compartment

5.4 Monitoring Results

Temperature monitoring began immediately after installation of each monitoring point. The monitoring of gases began shortly after completion of each compartment. Since the first gas samples were taken, problems were experienced with obtaining representative samples. The diameter of the installed gas sampling pipes was too big and, in the case of very long pipes, it was impossible to obtain a representative sample.

5.4.1 Results Overview

The following gases are sampled: CO, CH_4, CO_2 and O_2. The sampling of these gases is executed quarterly. Temperature is measured manually monthly. (The installed computer, radio-monitoring system for temperature monitoring is defective.)

Temperature Monitoring Results

Temperature monitoring of the first-year compartment with inter-burden from Benches 7A and 8 started during construction. This allowed the observation and analysis of the temperature fluctuation since material placement, before sealing took place, until the present. This is a time period of three years. ***Figure 5.20*** shows fluctuations in temperature (average of all monitoring thermocouples of all monitoring points) within the first-year compartment. Temperature monitoring of the plant discards compartment began after construction of the compartment. All monitoring points were successfully installed without convection problems at the monitoring points. Only one monitoring point, next to the north pit's high-wall, lost one of the four thermocouples that were installed within the monitoring point.

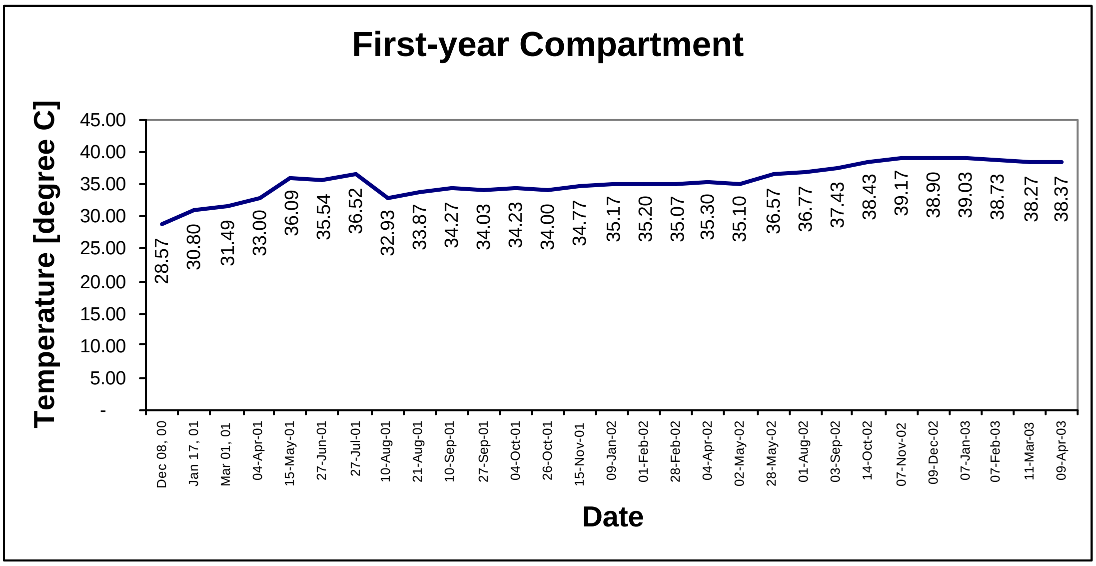


Figure 5.20: Temperature Fluctuation, First-year Compartment

Figure 5.21 shows the fluctuation in the temperature (average of all thermocouples of all monitoring points) within the plant discards compartment.

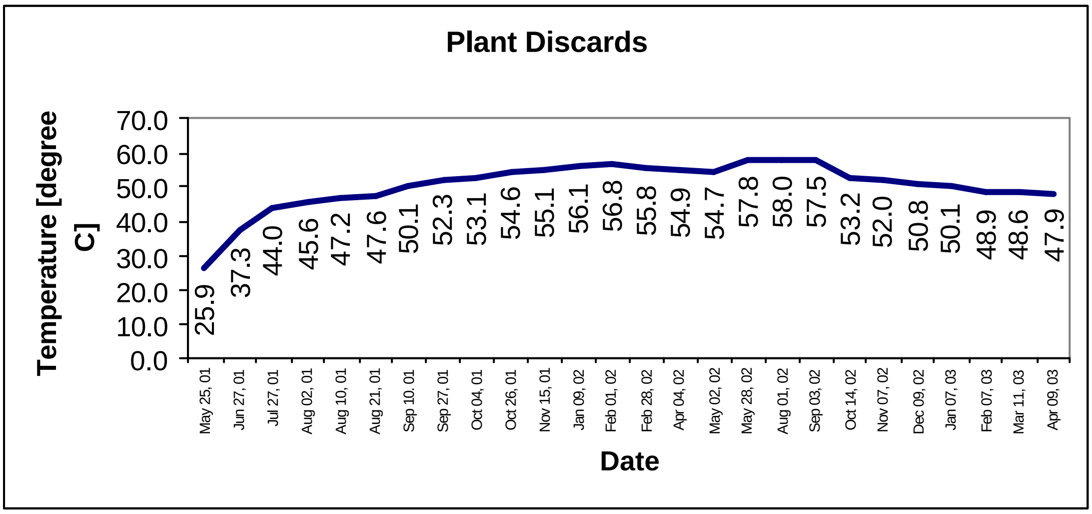


Figure 5.21: Temperature Fluctuation, Plant Discards Compartment

Temperature monitoring of the compartment with the inter-burden from Benches 7A, 7B and 8 commenced after construction. Three monitoring points were installed. A dozer damaged the first monitoring point during the night shift and it could not be recovered. The second monitoring point was installed successfully, but a few days after the installation convection occurred and all thermocouples and gas pipes had to be cut off. Only one monitoring point, next to the west sealing wall, remained. After the first temperature reading took place, it was discovered that only one thermocouple was operating within this monitoring point. Another three thermocouples were faulty and the technician could not repair them. ***Figure 5.22*** shows the fluctuation in temperature in the only one thermocouple installed in the compartment with the inter-burden (benches 7A, 7B and 8).

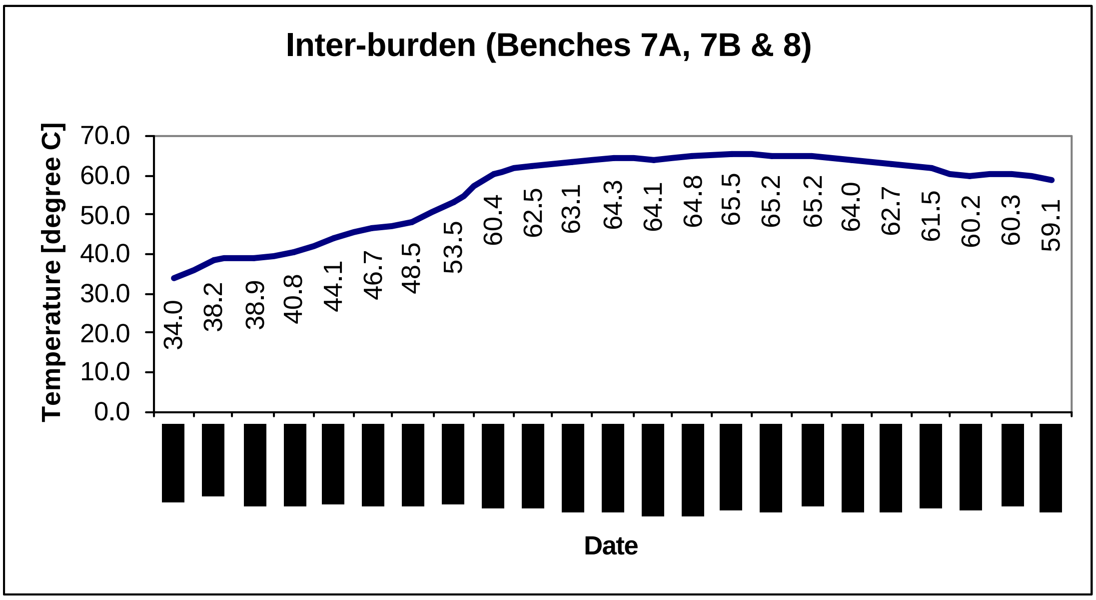


Figure 5.22: Temperature Fluctuation, Inter-burden Compartment

Gas Sampling Results

Gas sampling was very complicated from the start of the sampling. The hand pump that was used was inefficient in obtaining a representative sample. Furthermore, air leakage occurred from joins between the pipes and pipettes. The high cost of sampling and sample analysis did not allow this task to be redone in the same quarter. Therefore, many results were not obtained. The available results, however, show the oxygen level to be still too high due to leakages, as shown in ***Tables 5.2, 5.3 and 5.4.***

Monitoring Point	Point 1A/C	Point 1B/C	Point 1C/C
Gas Components	[%]	[%]	[%]
O_2	7.18	8.04	14.93
N_2	91.78	90.92	84.01
CO	Not detected	Not detected	Not detected
CH_4	0.0022	Not detected	Not detected
CO_2	1.092	1.112	0.455

Table 5.2: First-year Compartment, Reading (May 2001)

Monitoring Point	Point 2 A	Point 2 B	Point 2 C	Point 2 D
Gas Components	[%]	[%]	[%]	[%]
O_2	7.46	17.87	10.27	9.02
N_2	89.36	81.99	87.10	88.89
CO	0.0011	Not detected	0.0008	0.0007
CH_4	Not detected	Not detected	Not detected	Not detected
CO_2	3.177	0.143	2.627	2.087

Table 5.3: Plant Discards Compartment, Reading (July 2002)

Monitoring Point	Point 1 A	Point 1 B	Point 1 C	Point 1 D
Gas Components	[%]	[%]	[%]	[%]
O_2	9.58	8.86	8.94	9.60
N_2	89.40	90.12	90.05	89.38
CO	Not detected	Not detected	Not detected	Not detected
CH_4	0.0017	Not detected	0.0014	Not detected
CO_2	2.657	1.518	1.177	0.760

Table 5.4: Inter-burden, benches 7A, 7B and 8 Reading (April 2002)

5.4.2 Results Discussion

The gas sampling process was complicated as mentioned before. Technicians sampling the gases experienced leakages while sampling. The pipettes were not well designed to suit the piping system. The diameter of the pipes used to sample gases is 12.5 mm and is too big. With the length of the piping system being over 60 m, it is extremely difficult to obtain a representative sample. The technicians are in the process of improving the sampling method using the mechanical pump, but leakage of air still occurs. The budget for sampling is limited and, due to the very stable conditions controlled by temperature monitoring and monthly inspection of all backfilling compartments, further investment in the unreliable piping system is not required. The piping system was designed by the Iscor Metrology Department in 2000.

The available results from the gas sampling indicate very stable conditions of the cold oxidation. No dangerous concentrations of CO, CH_4 and CO_2 have been found. The oxygen level is not considered representative due to the poor quality of sampling and air leakages.

The very stable conditions are proven by the results of temperature measurements. The fact that the temperatures for the different materials almost behave as was predicted by the sealing theory is reassuring. No major peak differences were measured, although the values were higher than predicted using the sealing theory.

The temperature within the compartments containing plant discards and inter-burden from benches 7A, 7B and 8 fluctuates on a level that was theoretically calculated by the sealing theory in the previous sections, without taking into account the contribution of the age of the coal and the real balance between the heat generation and the heat dissipation. It is evident that the sealing layer limits the oxygen available to the oxidation process.

Rainfalls during April and May 2002, following a very dry summer, can explain the small range in temperature fluctuation, causing instability of moisture content. The very dry period since July 2002 until December 2002 can explain the temperature decrease within all compartments during this period due to very high vaporisation rate. The sealing layer was saturated by water after these rainfalls and the moisture increased during the next few months within all compartments. Moisture condensation as an exothermic process caused the small increase in temperature within the compartments (see ***Figures 5.21 and 5.22***), while the endothermic vaporisation process caused the decrease in temperature during the dry period mentioned above. Unfortunately, moisture cannot be measured and therefore cannot be taken into consideration in these models. Another factor contributing to this aspect is fluctuation in the barometric pressure. The season's temperature and moisture fluctuation is also visible within the first-year compartment, (see ***Figure 5.20***).

A monitoring system was also installed within the third-year compartment, which is not a part of the large-scale test. However, the material used to build the third-year compartment is the same as the martial used to build the first-year compartment of the large-scale test; the temperature is slightly higher than within the first-year compartment, see ***Appendix H***. The only explanation for this different behaviour is the construction of the compartment. The first-year compartment of the large-scale test was built using three sub-levels, while the third-year compartment was built as one 33 m-high level. Therefore, the compaction was worst within the third-year compartment, allowing much better segregation of the material due to the three times higher slopes. During the current construction of the forth-year compartment, using three sub-levels, a decision was taken to build the next compartments of inter-burden material (backfilling Level 1) using three or four sub-levels to allow maximum compaction and a minimum segregation of material to minimise the spontaneous combustion risk.

6 SUMMARY

6.1 Experience and Knowledge gained from this Theory's Application

Conclusions based on the laboratory tests, and on the mathematical risk model, enabled the development of a method that met the requirements for a safe backfilling method in terms of spontaneous combustion. The method described in "Backfilling into pre-built and sealed compartments with the fixed width of compartments" has been tested and implemented successfully during the large-scale test.

The very stable conditions within the sealed compartments of the large-scale test, a very reliable monitoring system and the high quality of the backfilling process (according to all assumptions of this thesis) allowed Grootegeluk Mine to continue backfilling the inter-burden material (benches 7A and 8) into the working pit. This theory works and is being used to formulate the current Backfilling Code of Practice. Not only does this method add value to the waste handling system, but it also reduces the environmental risks on the mine and therefore reduces costs.

The first-year compartment has remained stable and safe over the past 36 months. The plant discards and inter-burden containing bench 7b have remained, reducing the temperature over the past 25 months. It is therefore safe to conclude that the backfilling method has significantly reduced an environmental problem for Grootegeluk Coal Mine in terms of spontaneous combustion.

6.2 Applicability of this Thesis

The sealed-compartment method can be used by the coal industry to reduce the negative environmental impact of spontaneous combustion. The concept of sealed compartments can find application in all coal-storage facilities, such as coal terminals where coal is subject to a time risk and therefore also a spontaneous combustion risk. It is also a safe way of handling waste material inside the coal mining pit and thus not sterilising the surface area with a waste dump. This method can also be applied to surface dump conditions, where pre-built compartments can be used for the storage of reactive plant waste.

The sealing model is applicable to the entire coal mining industry provided that suitable materials are tested to determine a sealing method. The column test was designed to determine depletion of oxygen within a reactive material sealed by a layer of sealing material. The greater the depletion of oxygen (using the same reactivity and volume of reactive material), the better the sealing properties. The thickness of sealant required can then be determined for any type of reactive and sealing material using the above methodology. The acceptance of this method will also reduce environmental impacts and costs of rehabilitation, since dumping and sealing can effectively be accomplished during normal mining operations and need not be addressed at mine closure.

The sealing method, which restricts transportation of oxygen into dumps, should significantly reduce available oxygen that supports the burning process of all dumps at Grootegeluk. In November 2000 a sealing method was designed to control the fire within Dump 6. This dump was the most dangerously affected by combustion. Before sealing, Dump 6 exploded a few times per day, emitting toxic gases which were hazardous to the workshop situated about 500 m away. The temperature inside this dump was very high (about 1000 ^{0}C according to infrared plotting). An approximately 3 m thick layer of overburden material covered the surface and an about 10 m thick layer of the overburden material covered all the slopes. During the sealing process, the frequency of explosions decreased as well as the quantity of emitted gases. The sealing was completed in February 2002.

Dump 6 is controlled monthly and any cracks in the sealing layer are immediately handled. Infrared monitoring shows a significant improvement and no explosions are currently being reported. Furthermore, since completion of sealing no toxic gases were found around the workshop. This in itself proves the advantages of this model and the impact the right sealing material can have on the environmental conditions and a reduced health and safety risk.

The same method was used to solve a problem within the tyre dump. This is very small compared to Dump 6. The sealing process was completed from March to May 2002 and the same excellent results were achieved.

Currently, the same sealing method is being used to design a rehabilitation programme for Dump 3, Dump 4 and Dump 5. In terms of this programme, the sealing method must additionally prevent ingress of rainwater into the dumps to avoid ground water pollution.

6.3 Added Volume

6.3.1 Backfilled Volume

From 20 May 2000 to 30 June 2001, 7 068 064 t of inter-burden was backfilled (see ***Table 6.1***). Backfilled tonnages for the financial years 2001/2002 and 2002/2003 are shown in ***Tables 6.2 and 6.3***.

Bench	Budget Cumulative [t]	Actual Cumulative [t]	Variance Cumulative [t]
7A & 8	5 165 088	5 123 544	-41 544
10	1 546 956	1 944 520	+397 564
Total	6 712 044	**7 068 064**	+356 020
Total [%]	100	105.30	+5.30

Table 6.1: Backfilling during Financial Year 2000/2001, since 20 May 2000

Bench	Budget Cumulative [t]	Actual Cumulative [t]	Variance Cumulative [t]
7A & 8	5 229 623	4 938 334	-291 289
10	1 781 410	2 172 774	+391 364
Total	7 011 033	**7 111 108**	+100 075
Total [%]	100	101.43	+1.43

Table 6.2: Backfilling during Financial Year 2001/2002

Bench	Budget Cumulative [t]	Actual Cumulative [t]	Variance Cumulative [t]
7A & 8	3 442 784	3 578 810	+136 026
10	1 018 862	1 456 237	+437 375
Total	4 461 646	**5 035 047**	+573 401
Total [%]	100	112.85	+12.85

Table 6.3: Backfilling during Financial Year 2002/2003 (July – March)

In total, 19 214 219 t have been backfilled since the commencement of the inter-burden backfilling.

6.3.2 Savings

Previously, before the implementation of the backfilling method, the inter-burden material was dumped outside the pit. Because of the shorter hauling distances and the elimination of the vertical travelling distance of about 85 m, the cost of inter-burden handling was reduced by R1.310/t (data 2000/2001). Taking a 10 % cost escalation into account, the saving is estimated at R1.440/t for 2001/2002 and R1.584 for 2002/2003. Therefore, the backfilling method has realised savings to date of approximately **R27 474 674** (including March 2003).

6.4 Residual Problem

6.4.1 Minimum Knowledge required by Pit Superintendent

In future Grootegeluk's mining operations will under the supervision of different people. It is essential for the person in charge to have knowledge and an understanding of some few cardinal aspects in order to achieve the minimum skills level regarding the backfilling theory.

Every person in charge should be alerted to this research that showed that backfilling into pre-built and sealed compartments provided an effective solution for the Grootegeluk spontaneous combustion problem (see Figure 4.4).

The main requirements of the theory are:

- **Filling material into pre-built compartments** to isolate reactive material with a higher risk within slopes and to control combustion within one compartment
- **Building compartments with a fixed width** to maintain a constant stacking rate, determined by the risk model as the safe rate and to maintain a constant ratio between different types of waste materials
- **Sealing of the compartments** to isolate reactive material between levels and compartments to handle combustion within one compartment, in case of combustion
- **Isolating reactive waste from the pit's high-walls using layers of benches 10 or 1 material** to prevent transfer of combustion into the high-walls

According to this theory the main standards are:

- Slopes within the stacking (dumping) area cannot be exposed to open-air oxygen for longer than eight weeks.
  The eight-week period is adequate according to the critical time for slope exposure.
- The surface of any stacking level cannot be exposed for longer than three months to open-air oxygen.
  The three-month period is adequate according to the critical time for surface exposure.
- Stacking dimensions and stacking rate must adhere to the above assumptions.

Need for Monitoring and Control

Temperatures must be monitored monthly. If the temperature within any compartment reaches 70 ^{0}C, an urgent investigation must be held to determine the root cause of the increase. The area affected must be immediately checked for cracks, ripped and re-graded as well as compacted again. Cracks allow oxygen to penetrate the dump and therefore they must be dealt with immediately. An additional sealing layer must be added - an additional 1-2 m layer of overburden is recommended.

All backfilling boundaries, especially slopes and contacts with high-walls, must be checked monthly and, in the case of cracks appearing, the area must be ripped and re-graded. If necessary, if subsidence of material occurs, new sealing material must be added to level the area affected by the subsidence. After each new activity, the area must be compacted.

6.4.2 Minimum Knowledge required by Mine Planner

Reconciliation of the compartments' dimensions must be done according to the budget changes, if the ratio between the benches' liberation has been changed by more than 10 %. The probability of such changes is very low, however, due to the fixed geological conditions.

The new dimensions of compartments must provide a safe stacking/dumping rate for the safe exposure of reactive waste discussed previously.