ABSTRACT

The mineralised members of the Brockman Iron Formation mined at Mt Whaleback are overlain and underlain by shale horizons. To maximise resource recovery, waste movement within the life of mine plan will total approximately 3.3 billion tonnes.

Approximately 15 per cent of waste materials contain zones with varying amounts of sulfides and carbon and are referred to as ‘reactive shale’. Reactive shale has the potential to self-heat and can react with some explosives, resulting in spontaneous explosion. Sulfide rich zones also have the potential to generate acid rock drainage (ARD). Successful mining of reactive shale requires constant co-ordination between the geology, mine planning, mining and environment departments.

Safe storage of reactive shale is the focus of ongoing research. Since the mid-1990s, a number of trials have been undertaken at Mt Whaleback in order to further the understanding of the physical and chemical properties of reactive shale. This paper summarises some of these trials, and discusses key learnings arising from interpretation of results. Ultimately, the learnings from this research will provide the guidelines for successful storage of reactive shale.

INTRODUCTION

The Mt Whaleback iron ore mine is located adjacent to Newman, approximately 1200 km north of Perth, in the Pilbara District of Western Australia (Figure 1). The Pilbara District is a semi-arid tropical region with a mean annual rainfall of approximately 330 mm. It is common for rainfall to occur over short periods with high intensity. Annual potential evaporation typically exceeds 3500 mm.

Development of the Mt Whaleback mine commenced in 1968. The mine currently produces approximately 18 million wet tonnes of saleable product and 53 million tonnes of waste material annually. To date, some two billion tonnes of waste rock have been mined. Ultimately, some 3.3 billion tonnes of waste rock will be mined and located into Overburden Storage Areas (OSA) in and around the final pit.

The oxidised waste rocks at Mt Whaleback are geochemically similar and deficient in pyrite as well as carbonates (Campbell, 1996), and are classified as ‘inert’. The unoxidised waste rocks have varying amounts of carbonaceous matter and sulfide minerals. Approximately 15 per cent by volume of the waste rocks contain elevated levels of carbon and sulfides, with negligible carbonates and are herein referred to as ‘reactive shales’. The nodular zone of the Mt McRae Shale has sulfide values greater than 20 per cent.

SPONTANEOUS EXPLOSION AND COMBUSTION

Spontaneous combustion describes the chemical reactions where heat is generated spontaneously within a substance under conditions that prevent the dissipation of the heat to the environment. The temperature of the reacting solid will rise, leading in turn to an increase in the rate of reaction and greater heat generation. Left unabated, the accumulation of heat can lead to the ignition of the solid reactant (Humphreys, 1998).

Spontaneous explosion describes a series of reactions which can occur when weathered sulfides contact with ammonium nitrate fuel oil (ANFO) (Rumball, 1991).

The Mt Whaleback operations first reported burning shale in 1975. Investigations by Stevenson (1976) determined that the reactive shales were unlikely to constitute a hazard. From 1978 to 1983 several observations of burning shale were recorded. Investigations at the time linked the incidents to reactions with ANFO spills (Łukaszewski, 1978).

In 1983 two blastholes in reactive shale charged with ANFO, detonating cord and booster, spontaneously exploded (Rumball, 1991). Several investigations by BHP Central Research Labs, ICI and site personnel ensued. Additionally, Murdoch University was commissioned to undertake research into the chemical processes occurring which result in spontaneous explosion. Rumball (1991) concluded that all explosions and shale fires were the result of reactions occurring between ANFO and isolated sulfide rich zones of reactive shale.

The Sulfur Dioxide Task Group was established in order to apply the understanding of the investigations and research. This multi-disciplinary group developed the Pyritic Black Shale Procedures, which continue to be updated and are a critical part of the successful management of reactive shale at Mt Whaleback.
**Current practices**

Current mining practices have greatly reduced the number of mine fires in the pit and in OSAs over the last decade. The key processes are:

- Identification of 100 per cent of the potentially reactive material in blasthole drill chips.
- The use of inhibited ANFO in 100 per cent of potentially reactive blastholes.
- Mining of 100 per cent of the reactive shale patterns within three weeks of being fired.
- Placement of 100 per cent of the reactive shale in designated OSAs.
- Reactive shales with recorded temperatures greater than 50°C are loosely dumped to allow the reactive shale to cool. Rumball (1991) determined a critical mass of 2 m thickness is required for self-heating to continue.

**INTEGRATION OF REACTIVE SHALE MANAGEMENT**

Based on Rumball (1991) and the Sulfur Dioxide Task Group recommendations, OSA construction required that reactive shale be hauled to the most remote active tip head and diluted with inert waste, as shown schematically in Figure 2. The result of this practice is that most OSAs at Mt Whaleback have the ability to generate ARD.

This method of OSA construction changed in 1996. Based on the experiences of other operations in semi-arid climates with ARD material, Mt Whaleback adopted an encapsulation strategy for OSA construction, as shown in Figure 3. Additionally, the Government Works Approval for ARD dam construction directed that all ARD material being mined be dumped into the catchment area of the ARD dam, although it should be noted that this restriction was lifted in 1998. The shortfall with this approach is that the 2 m thickness critical mass for reactive shale is exceeded, and spontaneous combustion in OSAs can occur and continue unchecked.

The opportunity to create OSAs in-pit may occur in the future. Ideally, ARD material should be targeted for storage in-pit so that the potential for external run-off is minimised. However, the potential for spontaneous combustion (and resultant SO₂ emissions) requires that waste types used and OSA construction methods implemented have zero risk of spontaneous combustion potential. All future OSA designs will minimise the potential for spontaneous combustion and ARD to occur. The following work is underway to determine the most appropriate storage methods.

1. research to fully determine the mechanisms of spontaneous combustion;
2. computer modelling to assess the performance of different OSA construction methods;
3. instrumented field trials of alternate cover systems;
4. life of mine scheduling of reactive shale movement; and
5. identification of appropriate storage locations for reactive shale within the final closure landform to minimise the potential for rehandling at a later stage of the operation.

**INSTRUMENTATION OF OVERBURDEN STORAGE AREAS**

**Pond A**

A research project was initiated to conduct a preliminary field evaluation of the internal gas and temperature dynamics of an OSA containing pyritic shale. Backfilling of the Pond A OSA provided the opportunity to conduct a simple, and inexpensive, field research trial to develop a preliminary understanding of the internal dynamics of an OSA containing reactive shale.

An old tailings and water storage facility, Pond A, was identified as an ideal location for the storage of reactive shale. A design of two 15 metre vertical lifts was implemented, although the western side of the top lift was left exposed to allow for future mine development (Figure 4).
In April 2000, as the lower lift was emplaced, an area of the tip-head was isolated so as to allow for the installation of instrumentation down the rill face of the tip head. Large diameter HDPE polypipe (300 mm NB) was used to house gas lines, with outlet ports located approximately every two metres down the pipe. Thermocouples were also located at these ports (Figure 5).

Once installed, the tip-head was re-activated so as to bury the instrumentation within the OSA. In September 2000, the tip-head of the upper lift of the OSA had progressed to the location of the previously installed instrumentation. Once again, the section of the tip-head was isolated whilst the same instrumentation was connected to the lower lift, and extended to the top of the upper lift (Figure 4b). The tip head was reactivated and the upper lift completed. A gas and temperature data acquisition system was installed at the top of the dump. Approximately one year of pore-gas measurements, including \textit{in situ} oxygen (O$_2$), sulfur dioxide (SO$_2$), and carbon dioxide (CO$_2$) contents and \textit{in situ} temperatures, were collected from seventeen sampling locations from September 2000 to November 2001. The sampling locations were distributed between a lower lift (seven locations), a horizontal lift (three locations), and an upper lift (seven locations). Temperature readings from all points were recorded automatically every six hours. Gas samples were collected weekly from each sample point by pumping the gas through a portable chromatograph to record \textit{in situ} O$_2$, CO$_2$ and SO$_2$.

Monitoring ceased when it was confirmed that the polypipe had melted (the polypipe has a nominal melting point of 220°C). This rendered the gas lines ineffective and cast doubt over the reliability of the temperature data.

A generalised summary of performance based upon the field data collected at the Pond A OSA can be developed based on four stages of observed performance. Figure 6 conceptually illustrates the field performance data collected from the Pond A OSA during the four stages.
Stage One

This stage commences with placement of the pyritic shale into the OSA. The concentrations of gases within the pore-space represent atmospheric conditions (O₂ at approximately 21 per cent and negligible CO₂) as a result of blasting, loading, transport, and placement of the material. Oxygen is consumed during this first stage as evidenced by the drop in O₂ concentration shown in Figure 6 during Stage One, while at the same time CO₂ is produced. The decrease in O₂ concentration is essentially a 2:1 by percentage when compared to the increase in CO₂ concentration. Note that the production of CO₂ is a function of only organic carbon oxidation because in situ neutralisation of acid products resulting from pyrite oxidation, and the associated production of CO₂, is not likely. The material placed in the Pond A OSA has little to no acid consuming potential.

Oxygen consumption as a result of organic carbon oxidation, and the subsequent production of CO₂, occurs approximately on a 1:1 molar ratio (Bennet et al, 1995 and Seok et al, 2001). This ratio would also reflect in a change in the concentration of these two gases if it were assumed that the diffusion of CO₂ and O₂ were the same. In reality, diffusion of CO₂ would be somewhat slower given the same conditions because it has a slightly higher molecular weight. Therefore, the additional O₂ consumption resulting in the 2:1 ratio measured within the Pond A OSA is a result of pyrite oxidation. The energy released per mole of O₂ consumed as a result of pyrite oxidation is marginally greater as compared to that for carbon oxidation. Therefore, it is reasonable to assume that the constant in situ temperature increase measured within the Pond A OSA during Stage One is a result of an equal contribution from carbon oxidation and pyrite oxidation. In situ temperature during this first stage increased at a constant rate of approximately 2°C per week.

Stage Two

This stage is noted in Figure 6 as the initiation of a convective cell within the OSA. The first half of this time frame can be characterised by maintenance of reduced pore-gas O₂ concentrations and elevated CO₂ concentrations, as compared to atmospheric conditions. The O₂ concentration during the first half of this stage had dropped to approximately five per cent, as compared to atmospheric conditions which are approximately 21 per cent, while the CO₂ concentrations increased to about eight per cent, as compared to atmospheric conditions which are less than 0.1 per cent. A return to atmospheric O₂ and CO₂ concentrations occurs at a significant rate during the last half of Stage Two as the convective cell continues to develop. The return to atmospheric pore-gas concentrations within the Pond A OSA is a result of the convective cell ‘drawing in’ air from the atmosphere, most likely in a lateral direction from an exposed face of the Pond A OSA.

In situ temperature during Stage Two continued to increase at a constant rate of approximately 2°C per week. The total temperature increase from the onset of monitoring to the end of Stage Two was approximately 40°C to 45°C, as shown in Figure 6. Note that the initial in situ temperature after placement of the material into the Pond A OSA was approximately 25°C to 30°C.

Stage Three

This stage is characterised by maintenance of pore-gas O₂ and CO₂ conditions representative of atmospheric concentrations. A convective cell has been established, and self-heating of the Pond A OSA material in the region of the monitoring system is occurring during this stage because the material is dry and the heat cannot easily dissipate away from the reaction area due to the low thermal conductivity. Oxygen is still being consumed during this stage. However, the significant increase in temperature has resulted in the maintenance and enhancement of the convective cell and a continued supply of atmospheric O₂ to replenish any consumed during oxidation. The field data suggests that the high temperatures measured and the significant self-heating observed do not occur without a continuous supply of O₂. This implies that the mechanism for supplying O₂ from the OSA face to the reaction site (ie air permeability, flow length, and flow path) is a key factor influencing self-heating.

In situ temperature increases by nearly 150°C during Stage Three, to approximately 220°C by the end of the stage. It is important to note two points with respect to the measured temperature increase. First, the increase in temperature, both the rate and the ultimate temperature measured during Stage Three, was a function of the proximity of the monitoring equipment to the ‘centre’ of the zone of self-heating. Second, many of the in situ temperature sensors malfunctioned prior to as well as during the latter period of Stage Three. Therefore, it is not known whether in situ temperatures may in fact be higher than recorded, or have levelled off at approximately 220°C.

The evaluation of in situ data obtained during Stage One and Stage Two indicates that pyrite and carbon oxidation are equally responsible for the steady increase of in situ temperature until the onset of Stage Three. At this point, in situ temperatures have reached a level where a convective cell has been established. A continuous supply of O₂ is required in order for the convective cell to establish as well as maintain itself such that in situ temperatures dramatically increase to the level measured during the last half of Stage Three. The in situ air permeability and the length of the flow path are thus critical factors influencing self-heating of the Pond A OSA. An additional critical factor would be the poor heat dissipation characteristics of the OSA material.

Stage Four

A significant drop in O₂ concentration and an increase in the CO₂ concentration characterise this stage. It is unlikely that the supply of carbon and/or pyrite has been exhausted at this stage. In addition, even though the temperature sensors malfunctioned, it is reasonable to assume that in situ temperature is at or even higher than the most recent reliable measurements of 220°C. Therefore, the temperatures required to maintain the convective cell and draw in atmospheric air likely still exist.

It is hypothesized that a reduction in air permeability of the Pond A OSA material, at a single location, or at multiple locations along the primary flow path(s) as atmospheric air is transported from the face of the OSA to the reaction site, is the reason for the significant change in pore-gas composition. Field observations of material which has combusted demonstrates that the reactive shale undergoes a significant change in physical and chemical characteristics as a result of self-heating process. The material is initially a coarse-textured (but relatively well-graded) porous material. The material is altered after self-heating to a much finer-textured material, which has significantly different hydraulic properties, and can also undergo cementation if moisture is available. Air permeability will be significantly reduced as a result of the change in material properties. The collapse of the structure within the OSA and resulting internal settlement and consolidation will also impact on the air permeability.

Two-five-ten metre trial

Construction

In October 2000, a design for the construction of a trial reactive shale dump was approved. The objectives of the trial were to:

• test whether a ten metre vertical lift of net acid generating (NAG) material in an OSA is the most effective method of dealing with reactive shale;
test the ability of a four-metre thick cover system to withstand or control reactive shale self-heating;
• test the Rumball (1991) critical mass theory for reactive shale spontaneous combustion;
• examine inexpensive but effective ways to build field-scale trials, which are instrumented; and
• complement the Pond A instrumentation.

Construction of the trial commenced in late October 2000 and was complete in early December 2000 (refer Figures 7a and 7b). Instrumentation was placed into the dumps progressively as construction took place. For each ‘finger’, eight monitoring points were installed; four beneath the cover in the reactive shale, and the remaining four directly above the top of the reactive shale material (Figure 7b). At each monitoring point a gas port and thermocouple were installed. Gas lines were run through conduit pipe out of each ‘finger’ and to a central location to facilitate sample collection. All thermocouple wires were connected to an automated data acquisition system.

Results and interpretation

Monitoring commenced in early-2001 and continues today. Downloads of temperature, \text{O}_2, \text{CO}_2 and \text{SO}_2 are conducted monthly.

The two main findings from this trial to date are:
• no activity (ie heat and venting) was detected in the two metre reactive shale fingers; and
• visible venting of steam and gases on the five and ten metre thick reactive shale finger approximately six weeks post-completion, which was co-incident with the first rainfall since construction.

This trial is confirming the Rumball (1991) critical mass theory for reactive shale at Mt Whaleback. However, the effectiveness of a cover system to perform and maintain integrity over reactive shale is yet to be determined.

W05 hot monitoring

It was known that mining operations were planning to encounter ‘hot’ reactive shale (ie measured greater than 50°C in blastholes) from March 2001 to December 2002. This material was remnant from a wall failure in 1989. In order to alleviate operations problems at that time, a substantial amount (approximately three million tonnes) of inert overburden was dumped over this area so as to:

• geotechnically stabilise the area (albeit temporarily); and
• reduce the \text{SO}_2 emission emanating from fines burning uncontrolled in the failure area.

The effect was that the fires were left to continue to smoulder unabated for over a decade. As such, seven subsequent mining benches (each 15 metres high and on average 70 metres wide) encountered patches of reactive shale known to be ‘hot’. An immediate concern was what to do with the material due to the following issues:

1. emplacement into the ten-metre thick layer with hot, reactive shale on OSAs could be akin to ‘throwing a match into a tinderbox’;
2. dilution with inert material would be in effect a reversal back to previous practices; and
3. mine schedules of waste mining showed that for this entire period approximately 50 per cent of the waste would be inert material; hence there was a lack of significant waste material to dilute with reactive shale as per previous dumping methods.
Based on the work of Rumball (1991) and early confirmation from the two-five-ten metre trial, it was proposed that hot, reactive shale be dumped in ‘loose’ individual truckloads – see Figure 8.

This was considered best case for practical achievement of the 2 x 2 x 2 metre critical mass concept.

Several of the visibly venting loads were selected for temperature monitoring to confirm the effectiveness of the approach. This involved driving a galvanised steel pipe into the load, and taking weekly temperature readings – Figure 9.

The dumping strategy proved effective in 99 per cent of cases. For the odd persistent load, levelling and spreading with a dozer achieved the desired solution.

As surface on the OSA became a premium, additional space was required. A trial on previously cooled loads was undertaken to test if the material would re-heat – Figure 10. At three locations, monitoring points were established. Based on the success of this trial, a clearance was established for hot, reactive shale, which had cooled and was considered ‘dormant’. This dump will continue to be the location for hot, reactive shale material in the short- to medium-term.

CONCLUSIONS

• Spontaneous combustion probably occurs within OSAs at the Mt Whaleback site, and is now the subject of fundamental research by Curtin University School of Chemical Engineering.

• Management strategies for the emplacement of the reactive shale at Mt Whaleback must be integrated in considering best practice for both ARD and fires in OSAs.

• Much can be learnt from field performance monitoring of OSAs. Regardless of the degree of complexity involved in any field trial, it is critical that the project is completed in a planned and integrated manner with operations personnel.

• Field performance monitoring provides an opportunity to learn more than what had originally been the rationale for implementing the monitoring.

• Regardless of the developmental stage of an operation, there is significant value in field scale trials because the data provides an opportunity for all stakeholders to develop confidence in current and future mine waste management strategies.

Fig 8 - W05 dumping – hot reactive shale.

Fig 9 - W05 Temperature monitoring.
A critical mass of two metres (as proposed by Rumball, 1991) has been validated by field trials and operational use. If accumulations of reactive shale are less than two metres (in all dimensions) then spontaneous combustion cannot be sustained.

At Mt Whaleback, the opportunity to create OSAs in-pit may occur in the future. Ideally, ARD material should be targeted for storage in-pit so that the potential for external run-off is minimised. However, the potential for spontaneous combustion (and resultant SO₂ emissions) requires that waste types used and OSA construction methods implemented have minimal risk of spontaneous combustion potential. All future OSA designs will minimise the potential for spontaneous combustion and ARD to occur.

REFERENCES


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