Evolution of cover system design and waste rock management at a mine in the Pilbara region of Western Australia

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Abstract

Since 1995, cover system designs and waste rock management plans have been developed for the waste rock dumps (WRDs) at a mine in the Pilbara region of Western Australia. A major component has been investigation of acid metalliferous drainage (AMD) from the WRDs and development of management strategies to limit impacts to receiving environments. The site’s management strategies have focused on cover system design as well as landform and watershed designs. WRD landform design, and associated cover system design, has evolved several times since 1995. This has occurred in response to evolution of the conceptual models that have been developed at the site with respect to the mechanisms, and the controls on those mechanisms, resulting in AMD. The information gathered over a period of fifteen years led to changes in the conceptual model.

Prior to 1995, AMD was thought to be, in general, a ‘non-issue’ in arid environments similar to the Pilbara region. However, in 1995, the first appearance of AMD at the site occurred in response to a major cyclone. The first conceptual model for cover system performance was developed in 1995 with the main aim of limiting net percolation (NP) to the underlying WRD. This design was a ‘simple’ cover system that used the ‘moisture store-and-release’ concept, relying on evaporation to cycle moisture back to the atmosphere and a hummocky surface to limit runoff and runoff-induced erosion. At that time, no vegetation was included in the conceptual model as it was considered that bare surface evaporation would be sufficient. The conceptual model for cover system performance has evolved since 1996. The model still utilises the ‘moisture store-and-release’ concept; however, incorporating cover construction QA/QC, optimising transpiration through sustainable vegetation, and managing runoff through catchment design have been refined and incorporated into full-scale WRDs.

Since 1996, several research test piles, cover system field trials, and vegetation test plots have been constructed and monitored to measure their effectiveness in meeting AMD management objectives at the site. Fifteen years of data from the large cover system field trials constructed in 1996 and 2002 have resulted in key findings influencing long-term closure plans. NP into WRDs has been limited to 5% of average annual rainfall over 13 years of monitoring for a 2 m thick run-of-mine (ROM) cover system. Where a 4 m thick cover was constructed, NP has been limited to substantially less than 5% over 13 years. It has also been found that segregation of the ROM cover material, as well as selective handling of potentially acid forming wastes, strongly influences AMD management.

Short, medium, and long-term strategies were developed in 1996 to manage AMD at the site, identify mechanisms (and their controls) for AMD, and develop waste management practices to mitigate AMD. Short-term strategies that were introduced included containing runoff, identifying research goals, characterising the waste, and initiating management and rehabilitation plans. Research into strategic selective handling and placement of acid forming and non-acid forming overburden has also been monitored and evaluated. Long-term closure strategies are being implemented on site based on confirmation of the effectiveness of the field research and rehabilitation strategies.

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1 Background

The site operator has been completing closure planning support studies for the site since 1996. Closure planning has included the ongoing design of a preferred cover system for the waste rock dumps (WRDs) and development of waste management practises to mitigate acid metalliferous drainage (AMD). This paper presents a summary of the evolution of the cover system and waste management conceptual models that have been developed to mitigate AMD.

The site is an iron ore mine located in the Pilbara region of Western Australia, approximately 1,200 km N-NE of Perth. The ore deposit was discovered in 1957, mining of the deposit began in 1968, and it is estimated that there are 15 to 25 years of mine life remaining.

Research programs were initiated at the site in January of 1995 following the first evidence of AMD from the WRDs after a major cyclone. Research programs were intended to develop long term plans for decommissioning of the waste rock material at the site. There is currently approximately 3.3 billion tonnes of waste rock stored in WRDs on site. Ultimately, the operators will deposit a total of approximately 4 billion tonnes of overburden in WRDs constructed near the open pit. The nature of the waste rock has created particular challenges in effectively reducing impacts of the waste on its receiving environment. A description of the site AMD management plan can be found in Porterfield et al. (2003).

1.1 Climate

The Pilbara region is semi-arid with potential evaporation (PE) greatly exceeding rainfall on a yearly basis. The 100-year average annual rainfall at the site is 310 mm and average annual potential evaporation (PE) is approximately 3,000 mm. Strong seasonality is observed at the site with majority of the annual rainfall observed from November to March during the summer months. In addition, the highest PE values are measured in the summer months. However, during the winter months PE is substantially higher than rainfall resulting in an overall moisture deficit for the entire year. Rainfall has been directly measured at an WRD at the site since 1997. The 14-year average rainfall at the WRD is 444 mm.

1.2 Classification of waste materials

Overburden waste rock at site has been classified into four (4) categories described in Table 1.

Table 1 WRD waste characterisation

<table>
<thead>
<tr>
<th>Waste Class</th>
<th>Description</th>
<th>Approximate Percentage of WRD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A</td>
<td>Inert Overburden</td>
<td>82%</td>
</tr>
<tr>
<td>Class B</td>
<td>Overburden with sulphides between 0.3 and 1.0%</td>
<td>8%</td>
</tr>
<tr>
<td>Class C</td>
<td>Overburden with sulphides &gt; 1.0%</td>
<td>10%</td>
</tr>
<tr>
<td>Class D</td>
<td>Overburden with temperatures &gt; 50°C</td>
<td>&lt;&lt;1%</td>
</tr>
</tbody>
</table>

Approximately 10% of the total waste rock (Class C) is net acid generating (NAG). The majority of the NAG waste rock is found in a single shale unit. The shale unit also has the propensity to self-heat which is a result of the presence of pyrite. The shale is carbonaceous shale, and as such both the pyrite and carbon are subject to oxidation, which is an exothermic reaction. Temperatures greater than 600°C have been recorded within the WRDs as a result of spontaneous combustion. Shale fires and spontaneous explosions with ammonium nitrate fuel oil have also been recorded at the site, causing significant delays in operations (Waters and O’Kane, 2003).
2 Evolution of cover systems

2.1 Pre-1995

Prior to 1995 it was assumed that AMD would not occur at the site due to the arid conditions. It was thought that high PE at the site would result in little or no seepage from the WRDs. Therefore, no cover system would be required to limit AMD. Following large rainfall events in 1995, AMD was observed from the toe of a WRD. In response to this, research needs were identified in order to develop a revised conceptual model to address the AMD issue at the site.

2.2 1995

Following the first appearance of AMD it was determined a cover system was required to limit net percolation (NP) to the NAG waste within the WRDs. A research program was initiated to assess cover system design alternatives and waste management options. Initially, the primary research program included short, medium, and long term strategies. In the short term, the site identified the following research and operational needs in regards to cover systems:

- Research control and treatment options; and
- Initiate rehabilitation research.

On a medium-term scale to:

- Implement field research; and
- Measure the effectiveness of strategies.

And over the long term to:

- Confirm the effectiveness of short and medium-term strategies;
- Implement rehabilitation strategies; and
- Develop and implement closure solutions.

While efforts to contain runoff, characterise waste, and implement waste management plans were also undertaken, the authors’ primary focus was in researching control, treatment and rehabilitation options for WRDs. The development of technology for long term performance of WRDs with respect to vegetation, slope stability, surface runoff, erosion, and water infiltration was initially addressed by constructing cover trial test plots.

2.3 1996

2.3.1 Cover system field trials at WRD research site #1

The conceptual model for the WRD cover system field trials at research site #1 (Test Plot 1 and Test Plot 2) was developed based on the following assumptions (OKC, 1998):

- It is not feasible to limit the ingress of oxygen to NAG material within WRDs at the site.
- It is not practical to attempt to control the bacteriological activity within WRDs.

The conceptual model developed included a cover system that utilises the moisture store-and-release concept to control AMD. It was believed that the high evaporative conditions at the site would be sufficient in limiting NP to NAG material through moisture cycling within the cover system profile. Cover systems that utilise the moisture store-and-release concept are well established in mine waste closure planning for arid to semi-arid regions. O’Kane and Waters (2003) describe the moisture store-and-release concept for the the WRDs. Soil-atmosphere numerical modelling using site 30-year average climatic parameters was completed to determine a preferred cover system profile for the WRDs. The resulting preferred cover
system (1 m of run-of-mine (ROM) overburden over waste rock) was predicted to limit NP to less than 0.1% of average annual rainfall.

Two 1 ha field trials (Test Plot 1 and Test Plot 2) were constructed in January 1997 directly adjacent to each other on a horizontal surface at WRD research site #1. Well-graded ROM overburden material with little or no potential to consume or produce acid was used as the cover material. The cover material was block dumped (plug dumped) on the surface creating an undulating hummocky surface with low and high points as well as short surface runoff paths to reduce erosion during the life of the test plots. The hummocky surface was design to limit runoff from the WRO plateau surface such that all incidental rainfall would be contained to the plateau areas. A detailed description of the cover system design and construction can be found in O’Kane and Waters (2003).

Test Plot 1 (TP1) had a minimum of 2 m of cover material at the topographic low points while Test Plot 2 (TP 2) was constructed in two lifts with a minimum of 4 m of cover material at the low points. The performance of the two horizontal surface field test plots is monitored using a system designed to measure climate conditions at the test plot area (rainfall, potential evaporation, and actual evaporation), in situ moisture and temperature conditions within the cover and waste material, and NP from the base of the cover layer into the underlying overburden material from a large-scale lysimeter.

### 2.3.1.1 Performance monitoring

Cumulative change in water volume within the TP 1 and TP 2 covers is shown in Figures 1 and 2. Figure 1 also compares incoming rainfall and NP through the cover system profile on TP 1. Seasonally dependant moisture storage and release cycles are readily observed in both TP 1 and TP 2. TP 2 provided significantly more storage than TP 1, resulting in higher storage capacity and improved performance following three wet years from July 1998 to July 2001. Over approximately 13 years of monitoring, NP measured at TP 1 (2 m) has been 5% of annual rainfall while NP at TP 2 (4 m) has been less than 1%. This is different than the model predicted performance of NP<0.1% for a 1 m cover. The increased actual NP is likely due to high annual rainfall measured during the 14-year monitoring period (440 mm) compared to the long-term average (310 mm). Annual rainfall measured for 1998 to 2001, inclusive, was much higher than the 100-year average. In addition, the annual rainfall measured in 1999 (1,166 mm) was greater than the 100 year maximum previously recorded. Numerical modelling completed during the cover system design used a 30-year average annual rainfall to predict NP (i.e. modelling a single year); however, this method does not account for moisture stored from previous wetter-than-average periods such as those observed at the site. The cover system profile reached storage capacity following several years of above-average rainfall (1998 to 2001), which overwhelmed the moisture store-and-release system resulting in higher NP than predicted. The cover system profiles at TP 1 and TP 2 did not return to antecedent moisture conditions until 2008. Based on these results, it was concluded that a long-term variable climatic database should be used during the cover system design process to account for cumulative effects of annual rainfall.
Figure 1  Long term performance of TP 1 cover. Rainfall and net percolation amounts indicated are based on a October – September period to encompass the entire wet season.

Figure 2  Cumulative change in water volume at TP 1 and TP 2
During performance monitoring at TP 1 and TP 2 it was observed that a volumetric water content sensor placed at a depth of 190 cm had a greater response and shorter response time to a high intensity and magnitude rainfall event than a sensor placed at 100 cm. However, during smaller rainfall events the 100 cm depth sensor showed increased volumetric water content before the 190 cm depth sensor. It is likely that these data are indicative of preferential flow where a coarser zone was active during the higher rainfall event. During the smaller rainfall events, flow occurs through the finer matrix material.

The hummocky surface has the potential to promote rock segregation as larger size particles roll down to the toe of the hummock as it is placed. A schematic showing the areas where this type of preferential flow could occur is shown in Figure 3. This scenario was simulated using VADOSE/W to predict the effect of coarse rock segregation on a hummocky test plot. The results of the model are shown in Figure 4. The model showed the preferential flow through the coarse zone in addition to ponding at the base of hummocks in the coarse zone, and support the field observations and hypothesis that preferential flow in coarse textured zones of the cover material leads to higher than expected NP rates. These processes highlight the importance of implementing the cover system design by using appropriate construction practises. A cover system utilising the moisture store-and-release concept requires the placement of a homogenous cover material and prevention of material segregation during placement.
Based on the results of the TP 1 and TP 2 field trials, several key conclusions were made:

- Numerical modelling based on average climatic parameters does not reflect actual field conditions where variable climatic conditions influence cover system performance.
- Cover systems utilising the moisture store-and-release concept will return to antecedent moisture conditions given time.
- A cover thickness of 4 m is sufficient to result in low NP through the WRD cover system at the site.
- High NP may be observed years after peak rainfall (TP 1 2002-2003) due to pre-existing moisture conditions within the cover system profile.
- Looking at NP on a yearly time scale may not reflect the actual long term performance of the cover system as weather patterns operate on longer timescales.
- Relying on evaporation only is not sufficient to cycle moisture to the atmosphere; therefore, vegetation must be included to increase the moisture store-and-release capabilities of the cover system by evapotranspiration.
- Quality assurance and quality control (QA/QC) of cover system construction is important to ensure the cover system design is implemented properly.

### 2.4 Early 2000’s

Based on early results from the cover system field trials highlighting differences in performance between modelled and field NP rates, the cover system conceptual model for the WRDs was revised. The revised conceptual model maintained that a moisture store-and-release cover system would be the most promising closure option to control AMD. However, vegetation would be required to increase the evapotranspiration rates for the cover system. It was determined that the effect of vegetation on evapotranspiration, although known to be significant, had not been quantified at the site. As performance of moisture store-and-release cover systems rely on evapotranspiration, and therefore on the ability of vegetation to take up moisture, it was determined that quantifying transpiration rates would be required in order to improve upon the original conceptual model.

A second major assumption from the cover system field trials was that in order for cover systems to perform as intended, they must be designed on a site specific basis. As the main operations have satellite locations up to 400 km from the site, the issue of variability within similar climate areas needed to be addressed.

#### 2.4.1 WRD research site #2 and satellite location cover system field trials

The conceptual model for the WRD research site #2 vegetated field trials (TP 4, TP 5, TP 6 and TP 7) and satellite operation cover system field trials was developed based on the following assumptions:

- It is not feasible to limit the ingress of oxygen into NAG material at the site due to the semi-arid climate.
- It is not practical to attempt to control the bacteriological activity within WRDs.
- Transpiration is required to remove deeper moisture that cannot be removed by evaporation alone.
- Site specific evidence is required to obtain stakeholder confidence in cover systems that primarily rely on the moisture store-and-release concept to limit NP and function as a viable AMD management solution.
- A long term site specific climatic database must be used to understand and predict cover system performance.
WRDs plateaus should be separated into several sub-catchments to prevent runoff.

The conceptual model stated that a cover system that utilises the moisture storage-and-release concept with appropriate vegetation to encourage transpiration would be the most promising closure option to control AMD. A 4 m cover of ROM cover material was placed on the WRD research site #2 landform and covered with approximately 10 cm of topsoil in June 2001. The landform was then separated into several 0.25 ha bunded catchments with the intention of controlling runoff from the surface. A different vegetation treatment was applied to each bunded catchment. TP 4 monitoring station was installed on vegetation plot A1 and TP 5 monitoring station was installed on vegetation plot A2. In situ moisture conditions and meteorological parameters are measured at TP 4 and TP 5. A schematic of the cover system and performance monitoring system is shown in Figure 5. An aerial photograph of the WRD research site #2 landform is shown in Figure 6.

The assumptions regarding the conceptual model required that site specific evidence would be needed to obtain stakeholder confidence in cover systems that utilise the moisture store-and-release concept as a viable AMD management solution for sites other than the main operations. A full-scale cover system similar to WRD research site #1 and #2 was constructed at a satellite location WRD to determine short-term performance of the system in response to varying climatic conditions.

Figure 5  Schematic of cover system at WRD research site #2
2.4.1.1 Performance monitoring

Ongoing monitoring at TP 4, TP 5 and the satellite operations cover system since 2001 has shown similar cover system performance to TP 2 on WRD research site #1. Moisture cycling was observed and cover system profiles returned to antecedent moisture conditions following the wet season. Since TP 4 and TP 5 have been built, annual rainfall is closer to average with the wettest year experiencing 594 mm of rainfall (2005). It remains to be seen how transpiration rates would affect net percolation in an extremely wet year or years as experienced from 1998 to 2001. Quantifying transpiration rates of native species will result in better model predictions of performance. It appears that despite climatic and material property variations between the satellite and main operations, there is a range of materials that will provide sufficient storage capacity for a store-and-release cover at climatically similar sites.

Based on the results of the TP 4, TP 5 and satellite location field trials, several key conclusions were made:

- Vegetation has a positive effect on cover performance, but transpiration rates have yet to be quantified for native species.
- A cover system that utilises the moisture store-and-release concept is appropriate for sites with similar climatic conditions to those at the site; however, appropriate cover materials must be used.
- Construction QA/QC is imperative to good cover performance; segregation of ROM material due to poor QA/QC procedures can compromise cover performance due to preferential flow.

2.5 Late 2000’s – current conceptual model

2.5.1 W29 and naturally vegetated site performance monitoring

Two additional performance monitoring sites were installed in the late 2000s. TP 6 was installed in November of 2007 on the WRD research site #2 vegetated landform in catchment A3. TP 7 was installed at a naturally vegetated site east of the site’s open pit in June 2008. In situ moisture conditions and transpiration rates of natural woody species are measured at TP 6 and TP 7. Ongoing studies are being completed to determine the rooting characteristics and transpiration rates of native vegetative species.
2.6 Conclusions: evolution of cover system conceptual model

Ongoing performance monitoring of cover system field trials at the site has provided a rational basis for the evolution of conceptual models. These studies have provided a clear understanding of the need for cover systems for long term management of NP to and seepage from the WRDs. Key findings of the ongoing performance monitoring program include:

- High level of confidence with required cover system profile thickness with an adopted cover system design thickness of 5 m (based on performance of the 4 m thick cover system field trials).
- Construction QA/QC is paramount to ensuring implementation of design.
- Establishment of sustainable vegetation is a key to ensuring a cover system that utilises a moisture storage-and-release concept functions.

An ongoing research objective includes determining and extensive understanding of native species and transpiration characteristics. In addition, linking of NP to impacts on the receiving environment is required.

3 Evolution of waste rock management

3.1 Pre-1995 to 1996

Before the first evidence of AMD at the site, there was little control on management and placement of waste rock on site. The main considerations prior the first observance of AMD were managing exothermic waste material and associated spontaneous explosions and combustion. Figure 7 shows a typical WRD with a layered profile as a result of end dumping practices typical of operation before 1995. NAG material was dumped such that direct contact with the underlying natural ground occurred. AMD was first observed from the toe of an WRD in 1995 following high rainfall events during a major cyclone. As a result, waste rock management needs were identified in order to develop a new conceptual model that would address the AMD issues at the site.

![Figure 7 Typical WRD profile pre-1995](image)

3.2 Late 1990’s

Prior to 1995, little was known regarding internal dump dynamics and site hydrology that resulted in AMD from the toe of the WRD. Conceptual models were therefore based on the following assumptions:

- AMD is occurring at the toe of WRDs from rainfall landing on the WRD footprint.
- Very little is known about internal dump dynamics, structure and composition.
- Very little is known regarding waste composition and geochemistry.
Due to the immediate nature of the AMD problem, water treatment strategies were adopted immediately to control the release of AMD to the environment. Meanwhile, research programs were initiated to fill in the unknowns identified as outlined in Section 2.2.

### 3.2.1 AMD dam and evaporation ponds

To address the immediate problem of AMD from seeping from the WRD, in 1995 the site constructed an AMD dam adjacent to the WRD to capture all seepage reporting from the toe. The AMD dam capacity (850 ML over a surface area of 32 ha) was determined based on the assumption that the catchment area corresponded to the WRD footprint. However, following further high levels of rainfall it was observed that overland flow from a catchment upstream from the WRDs was flowing through the base of the dump and coming into direct contact with NAG material. As a result, the AMD dam capacity was not sufficient to contain all toe seepage, therefore evaporation ponds (560 ML and surface area of 56 ha) were constructed in 2000 to contain additional seepage and prevent discharge of AMD from the site.

### 3.2.2 Encapsulate and raising of NAG waste

In light of the new information regarding flow patterns under the WRDs, a new approach to designing WRDs was developed. In order to reduce contact between NAG waste and water flowing under the WRDs, a five metre inert waste rock base layer was placed on original ground prior to any NAG waste being placed. Next, NAG waste was encapsulated in inert overburden as seen in Figure 8 to provide non-acid forming (NAF) interim cover materials and limit seepage into underlying NAG material during construction of the WRD. A second requirement (not shown in the Figure 8) included that the thickness of the inert overburden side layer be great enough that rainfall landing on the crest of the WRD could travel vertically to the bottom of the WRD without contacting NAG waste (i.e. the crest of the inert overburden must have a lateral extent greater than the toe of any NAG waste). It was anticipated that by raising and encapsulating NAG waste, flow paths would exist such that contact between incident and upstream water and the NAG waste would be reduced resulting in lower total AMD from future WRDs.

![Figure 8](image_url)  
**Figure 8** Schematic of encapsulation technique for the WRDs
3.2.3 **Modular Mining Truck Dispatch**

In 1996, a modular mining truck dispatch system was introduced at the site. This system was initially incorporated in order to maximise truck efficiency when hauling waste by minimising haul distances. GPS systems were added to haul trucks to track their haul routes. In 1997, once material characterisation of waste rock was completed, it was determined that the GPS modular mining dispatch system could be used not only to minimise haul distances, but to preferentially dump separate classes of waste materials. Waste classification now occurs as the waste is being extracted and the waste can then be tracked to its final dump location. This provides a means to effectively execute the encapsulation technique and provides knowledge as to the internal structure and composition of new WRDs, both of which were identified as unknowns.

3.3 **2000’s**

Based on the knowledge gained from the studies and management techniques previously discussed, the conceptual model for waste rock management in the 2000’s was revised. A refined conceptual model was based on the following new assumptions:

- AMD is occurring at the toe of WRDs from a combination of NP through the dump and upstream water flowing under the WRDs.
- Very little is known about internal dump dynamics, structure and composition in WRDs built before 1997.
- Very little is known regarding waste composition and geochemistry in WRDs built before 1997.
- Strategic placement of materials using construction techniques such as encapsulation is integral to limiting AMD due to seepage and upstream flow through.

Since the immediate release of AMD was being controlled by evaporation ponds, more long term solution studies were initiated to prevent the occurrence of AMD, rather than treating AMD.

3.3.1 **WRD research location #3 soak area (2010)**

In the late 1990’s evaporation ponds were built as a short term management strategy of AMD from the WRDs. As the site’s research program progressed, it was found that diverting AMD to evaporation ponds was not a viable long term strategy for closure as they would require maintenance in perpetuity. The WRD research location #3 soak area was therefore commissioned to capture and contain overland flow upstream from the WRD landform that historically seeped, preventing flow-through seepage and decreasing the volume of water to the AMD dam.

The soak area consists of an extension of the WRDs into the upstream catchment with inert waste material (Figure 9). The area was divided into 1 to 2 ha irregular sub-catchments with wide bunds. The soak area gently slopes away from the original WRD footprint that was seeping to ensure runoff moves away from the WRD should a bund system fail. Each sub-catchment was seeded with native grass and shrub species. Conclusions on the functionality of the WRD soak area are not able to be made due to the recent commissioning of the area. However, the aim of the WRD soak area is to contain all seepage sourced from upstream catchments outside the footprint of the WRDs.

The site decided to construct the WRD soak area to minimise long-term risk of AMD from the historic WRD seepage. This required a change in the mine plan and substantial overhaul costs for placing the material at this location. However, this was deemed to be a preferred alternative to potentially managing AMD seepage in the AMD dam and evaporation ponds in perpetuity.
3.4 Waste Rock Management Conclusions

The site has adopted a system that integrates WRD construction (i.e. mine planning) and closure planning. The system includes management of WRDs previously constructed prior to strategic placement of mine waste (i.e. the WRD soak areas) as well as integrates current dump construction (NAG encapsulation) with mine waste production. Waste management also includes provision for cover system construction, which currently consists of a 5 m thick inert waste rock cover system on the WRDs. The result of the concurrent implementation and planning strategies is an incremental cost for closure of the site during operations, which will result in a long term cost reduction for overall closure of the site (life of mine 15 to 25 years).

Acknowledgement

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References