

BEYOND THE PAF CELL

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ABSTRACT

For many mining operations the PAF cell is the default solution to dealing with problematic waste. Historically this solution has allowed mine planners to adopt a position in the short term that any problematic material can be dealt with at any point in the mine schedule. In addition the blanket use of "engineered covers" as long term closure solutions allows the deferral of acid mine drainage (AMD) risk mitigation to mine closure. The net result is that the mine schedule is often prepared with little consideration of AMD issues which have been "risked" away.

However this approach may in many cases be leading operators to misprice the level of risk that AMD issues can present, even in the short term, due to a number of reasons such as early closure and the presence of fast reacting materials. In addition this approach also seems to be at odds with the general international principles of risk management which are grounded in the accepted view that prevention is better than mitigation.

To assess alternative options for waste management at a site in WA, O'Kane Consultants (OKC) carried out an assessment and design for co-disposal options of PAF. With an integrated approach to AMD management and working closely with site geologists and mine planners, co-disposal options have been proven to be compatible with the mine schedule. In addition detailed geochemical testing including kinetic testing carried out at the planning stage to support co-disposal has allowed the AMD risk profile to be better quantified over life of mine.

Passivation of sulfide oxidation reactions (leading to reduction in short term AMD risks), is for example a key benefit of co-disposal that can be demonstrated as a result of kinetic testwork. Additionally long term risks are shown to be reduced due to less reliance being placed on a "final cover solution" as a result of progressive compact and lift construction techniques.

1.0 INTRODUCTION

Acid and metalliferous drainage (AMD) is arguably the most significant "liability" that mining companies retain post closure. Management costs for AMD have been estimated globally at approximately \$US 1.5 billion per annum. (Lottermoser 2003). The total worldwide acid mine drainage liability for both historic and operational mines has been estimated at in excess of US \$10 billion (Lottermoser 2003). Total costs in Australia have exceeded \$US 500 million to date (Australian Nuclear Science and Technology Organisation 2003).

There are two major factors that have resulted, and arguably still are resulting, in AMD liabilities being created at mine sites.

- AMD problems often reveal themselves at a late stage in the development of a mine, in some cases they may not be evident for many years after closure (or potentially after abandonment). As a result of the 'lag' that may occur before AMD impacts are evident, environmental and financial risks are heavily weighted to the mine closure

rather than operations period of the life cycle of the mine. A result of this lag time AMD risk is often underestimated by operators as there is a link made between the observation that there is “no problem at this time” to a conclusion that there “will be no problem”. The presence of this lag effect therefore tends to foster complacency at sites where significant future problems may be a few years around the corner. The management of AMD is consequently impacted by the effect this lag time has on decision making as short term thinking does not translate well to long term issues like mine closure.

- In the planning stages of a mining project, fundamental decisions are made about the operation including waste storage and management. Although the fine detail has not yet been developed, conceptual designs are drawn up which commonly include footprints and designs for waste rock dumps (WRDs) and tailings dam (TSFs). This can prove to be a problem as it is still not routine for the use of geochemical modelling of AMD-classified material in conjunction with the early planning and scheduling of mining activities. A result of this is that concept designs are conceived before detailed geochemical assessments have been completed. A consequence of this “design before facts” approach is that retro fitting of the concept designs is then required if an AMD problem is identified later on.

The consequence of these two factors has been the proliferation of the use of PAF cells for management of PAF materials. This is because:

- A PAF cell can be “retro fitted” into almost any waste rock dump
- Poorly designed PAF cells may not result in any notable impacts for many years therefore problems can be “hidden”

The use of PAF cells for these reasons could be described as reverse engineering. The primary design consideration for the storage of PAF material should be aligned with industry best practice which, based on the international principles of risk management, are grounded in the accepted view that prevention is better than mitigation. The PAF cell in many cases does not meet this most basic principle.

2.0 PLANNING FOR FAILURE

Some planning issues that commonly result in poor decision making with respect to waste materials management include:

- Designs from a previous operation, or stage of mining at the site are “copy and pasted” using a “one size fits all” approach. This may then result in many stages of retro fitting and reverse engineering to make the design “fit for purpose”.
- Material(s) that were assumed to be suitable for construction purposes are later classified as unsuitable due to AMD risks. This may result in a significant loss of construction materials
- The volume of material that requires management as a result of AMD risks is significantly underestimated at the planning stage. This can result in the design of containment facilities at a late stage of planning. This in turn may result in significant cost and/or time delays as design metrics like footprints and/or height restrictions for waste dumps may already be set by planning consents.
- A key assumption is made during the approvals process that effective management of AMD material can be achieved by construction of a PAF cell. This may not be an appropriate means of management however if PAF material will be produced in small

volumes over a long time period. The construction and management of a single PAF cell is not practical over this timeframe. As a result the management measure proposed may be ineffective with respect to managing AMD risks.

- An early stage mining proposal is introduced during the planning process (for example an early ore mining option to generate positive financial returns). Planning decisions for AMD management may therefore be expedited. This may result in management measures being proposed that are not compatible with further stages of mining.

As previously stated, these issues generally conspire to the adoption of the PAF cell as the “solution” to PAF management. This would not be an issue if the PAF cell could be ubiquitously used as an effective solution, however there are a number of key reasons why this is not the case:

1. PAF cells are not generally engineered containment facilities. The common term used in industry is “encapsulation” however this is misleading as it implies a degree of engineered containment. In reality PAF cells are merely buried waste masses.
2. PAF cells rely on cover systems that reduce infiltration to function as they are not engineered structures. Any infiltration into the WRD will flow into a PAF cell unimpeded. However cover systems are placed on the surface of WRDs which is the most common failure point for these structures due to erosion/vegetation loss/weathering etc. The factor of safety for a PAF cell is often only as high as that of the cover system which in many cases does not offer a high factor of safety over long term time frames. (Wilson ref)
3. The internal structure of a WRD as a result of crude dump construction methods results in the formation of internal hydrology/gas regime that does not conform to the assumptions made when the PAF cell was “designed”. In simple terms oxygen comes from under the PAF cell in the dump not from the surface and water can come in from the sides.
4. Waste dumps are not routinely equipped with internal monitoring equipment making it difficult to validate the performance of the design
5. Construction of waste dumps at many sites is not completed with detailed QA/QC control and documentation measures. Cover systems are often proposed to limit infiltration into the WRD, however the most common failure point on a WRD is at the surface. As a result cover systems have an inherently low factor of safety in design in many instances.
6. The waste schedule is not compatible with the PAF cell design resulting in PAF materials that come out of the pit:
 - a. Too early
 - b. Too late
 - c. In too much volume
 - d. Are very reactive and so can't be left exposed for long periods

3.0 WRD DESIGN ISSUES

Some of the key issues that have an impact on the design of PAF storage facilities within WRDs and the success (or otherwise) are summarized below:

3.1 WRD structure

Generic conceptual models for WRDs have been published by many authors, and many guidance documents contain “industry standard” schematics. However, what may appear to

be a useful concise summary “picture” is potentially dangerous if these are assumed to be based on complete and robust technical models. Some authors have attempted to incorporate field data and scaled laboratory experiments to make these models more technically robust (notably the work of Ward Wilson, e.g. Wilson 2011), however this approach has yet to translate to the more generic “industry standard guidance”.

Figure 1 is taken from Australian Government DITR (2007) and clearly shows the limits of a generic model. For example the oxidized zone is shown as a simple halo around the edges of the waste, and infiltration is indicated to be vertically uniform. Whilst potentially applicable to homogeneous waste materials such as tailings, this model is not likely to be reflective of waste rock dumps. The location of a standard PAF cell is indicated on this Figure which is positioned to reflect the understanding of this conceptual model, i.e. that the middle of the dump is the best place as it is “encapsulated” from oxygen and water ingress.

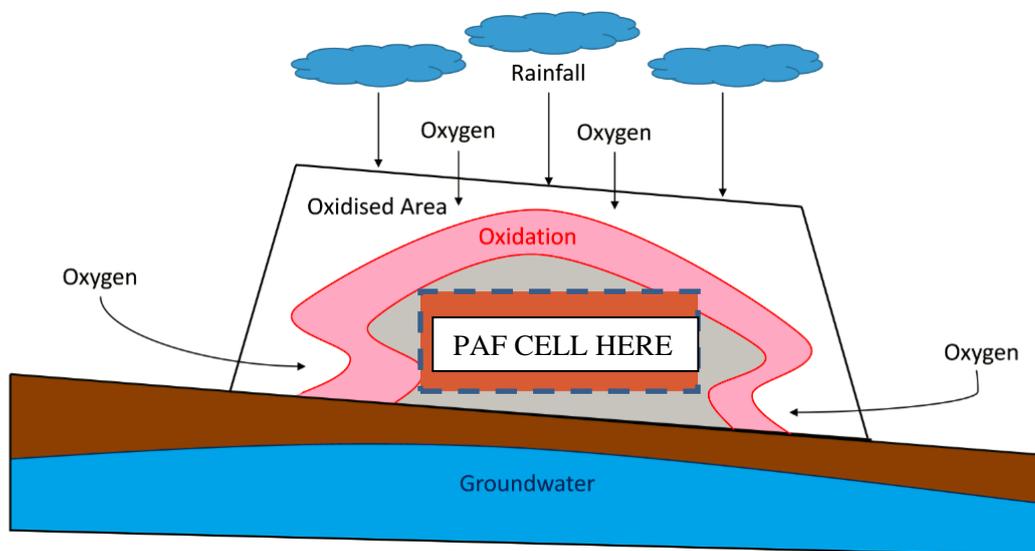


Fig. 1. Generic model of AMD production and contaminant migration from a waste rock dump after Australian Government DITR (2007).

The conceptual model shown in Figure 1 is commonly used for decisions on PAF cell placements however this model does not reflect the internal structures of dumps created as a consequence of the prevalence of end tipping material. These structures have intrinsic hydrologic characteristics which control oxygen and water flow throughout the waste material (Wilson 2011). Figure 2 is a conceptual model showing a cross section of a typical WRD constructed by end dumping material. The segregation of coarse and fine grained material into parallel bands along tip faces is a common feature of end-dumped WRDs. The segregation of material as shown in Figure 2 has been confirmed by WRD excavations in the work of Wilson (2011). The conceptual cross section shows that the infiltration of water enters the WRD at the top of the pile, percolating down through areas of fine grained materials. During heavy rain events such as cyclones, water will also enter the WRD in coarse grained sections quickly percolating to depth. Oxygen ingress primarily will enter the WRD at the bottom of the pile moving upwards through the free draining coarse material layers.

The presented conceptual internal structure of WRDs constructed by the common practice of end dumping is an ideal scenario for the production of AMD given the ample supply of atmospheric oxygen and water.

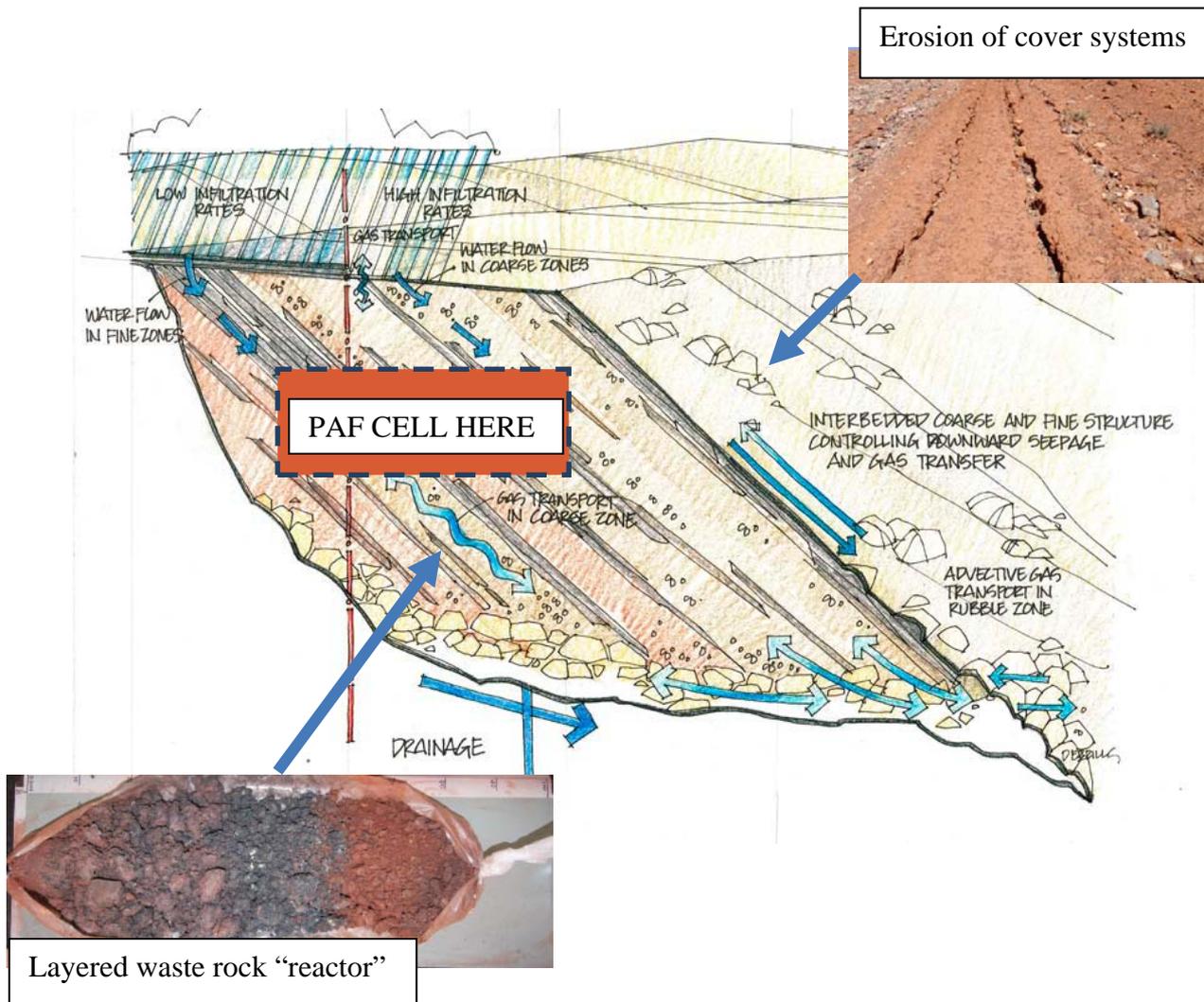


Fig. 2. Conceptual cross section of end dumped WRDs illustrating oxygen and water transport

3.2 WRD design

In contrast to other engineered waste management structures like domestic landfills, construction and regulator approval of WRDs commonly does not include detailed engineering specifications, as built drawings and QA/QC documentation. This has resulted in many WRDs being constructed poorly and often with limited planning/thought having been made with respect to materials management and placement. This is no clearer than the prevalence of end tipping in the construction of WRDs. End tipping as has been shown previously creates the perfect conditions for AMD to occur within a dump. Even when an un-engineered unlined PAF cell is proposed within a WRD, end tipping is still used to construct the dump, and in some instances the PAF cell itself.

In general PAF cells rely on cover systems that reduce infiltration into the WRD to function as they are not engineered structures and so are vulnerable to ingress of water and/or oxygen. This means that PAF cells are not actually the management measure to protect against AMD in their own right, rather it is the cover system that is the management measure. This is because any infiltration, or oxygen ingress into a WRD will flow into a buried PAF cell unimpeded as there is generally no “containment structure”. Many successful engineered cover designs have been implemented so the reliance on the cover system cannot be seen as a significant risk in all instances, however the fact remains that the most common failure point on a WRD is at the surface. As a result many cover systems have an inherently low factor of safety in design compared to alternatives such as truly engineered containment systems and layered co disposal options (discussed herein).

3.3 WRD monitoring

In contrast to other waste management industries such as domestic landfill, WRDs are generally not subject to active monitoring by way of internal instrumentation being installed (with the exception of cover systems). This “walk away” approach has resulted in the creation of potential environmental hazards as processes like AMD take many years to develop and often will go undetected for decades until a significant AMD discharge occurs without warning.

With the advancement of sonic drilling technology WRD can be assessed at depth to evaluate:

- Internal hydrologic conditions and the response of the WRD to climatic variables such as incident precipitation and pressure
- Internal processes such as heat generated through sulfide oxidation
- Movement and replenishment of oxygen through dump structure
- The location of dump structure such as rubble zones and underlying historical drainage pathways etc

The placement of oxygen probes, and pore pressure piezometers would allow the performance of the PAF cell to be monitored over time, although this at present is not industry standard practice.

3.4 Waste schedule

There are a number of planning factors related to the mine schedule that can make PAF cell use challenging:

- Waste schedules are not always produced, or are generally not very accurate with respect to AMD volume calculation or the time over which PAF will be produced
- PAF may be excavated early in the mine life before there is a suitable place to locate a PAF cell due to WRD construction limitations
- PAF may be excavated late in the mine life and disposal requires re-excavation of the waste or near surface disposal
- Reactive material requires immediate cover and, PAF cells may have been designed to be open for long periods which increases the exposure of the material to oxidation reactions
- A PAF cell looks simple on a schematic but the designation of one (or a few) areas for PAF deposition will restrict the operator to placement of PAF in very small area of the dump that may not be compatible with the mine schedule.

- The production of PAF may not be as planned in the schedule and so a designated location in the WRD may not be accessible.
- More PAF may be excavated than thought and so the cell will be filled faster than thought. Additional “cells” are then required in areas not previously planned for PAF disposal.
- A detailed waste schedule may not have been created at the time the design needs to be completed for the dump. The location and size of PAF cells may therefore not be appropriately designed.

An example schedule is shown on Figure 3. Although the volumes of PAF are not large, it is only once the waste schedule is viewed that the management challenges become apparent. From this figure it is clear that if PAF production occurs later on in the schedule and therefore a PAF cell is proposed, it may have to be close to the surface of the WRD if construction is from the bottom up as is standard practice.

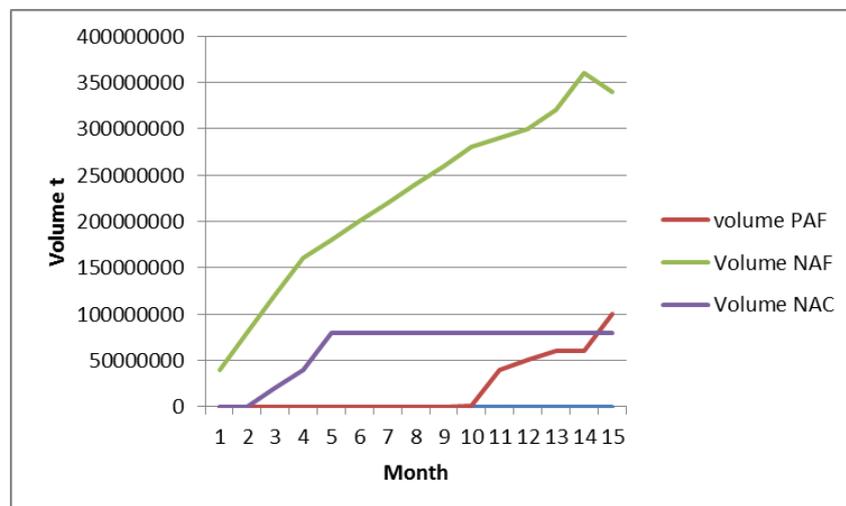


Fig. 3. Example of mine waste schedule from mine waste model (Pearce et al 2012)

4.0 CO DISPOSAL AS AN ALTERNATIVE

Co disposal has been used as a design alternative to cells for a number of years however the practice is not wide spread. The main reasons for this are that co disposal options are considered to be:

1. More expensive than a “containment cell”
2. Not compatible with the mine schedule
3. Too complicated to build

These are mainly issues relating to practical site management and planning issues, all three of these pre conceived “problems” are however not necessarily correct.

1. It is true that a co disposal option is more expensive in the short term and requires a more complex engineering design than a traditional PAF cell. However given a crude PAF cell is only one step above do nothing option then the cost base is not an applicable comparison. In addition the cost of placing and maintaining a complex

- cover system is often not taken into account, nor are the long term closure liability costs of the “failure” of the PAF cell that could result in AMD.
2. A co disposal option may in fact be more flexible and therefore compatible with the mine schedule than a PAF cell as multiple depths/areas can be used for PAF deposition. Scheduling problems with PAF cells include:
 3. Design complexity and engineering challenges of placing and maintaining a complex cover system to perform over decades/100s years to reduce infiltration (as PAF cells rely on this assumption) are often not taken into account.

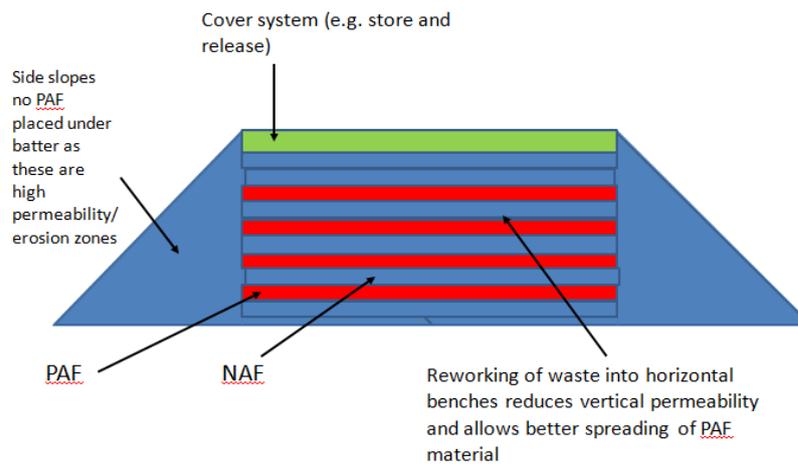


Fig. 3. Concept co disposal option

The general concept of co-disposal is to include:

- Horizontal layering to reduce vertical permeability and consequently oxygen and water ingress
- Co mingling of PAF and non acid forming (NAF), preferably with buffering properties to reduce the reaction rates of the PAF material
- Less reliance on the cover system to perform adequately as a mitigation measure for AMD

5.0 EXAMPLE OF CO DISPOSAL OPTION

OKC assisted with the management concept for a site in WA which required management of PAF materials. Details of the site are as follows:

- PAF materials were identified in the geological block model as pyritic banded iron formation (BIF)/chert in relatively small quantities <10%
- Kinetic testing indicated the materials were fast reacting as they have no buffering capacity
- Leach testing identified metals release as a low but potential risk if oxidation of the PAF materials occurred
- The mine schedule incorporated a geochemical block model which predicted that PAF materials would be produced over much of the life of the operation due to the location of the material in the pit shell

- Disposal under the slopes of WRDs was required

A PAF cell was not deemed to be a suitable option given the parameters of the site, instead a co disposal option was investigated as a potential design solution.

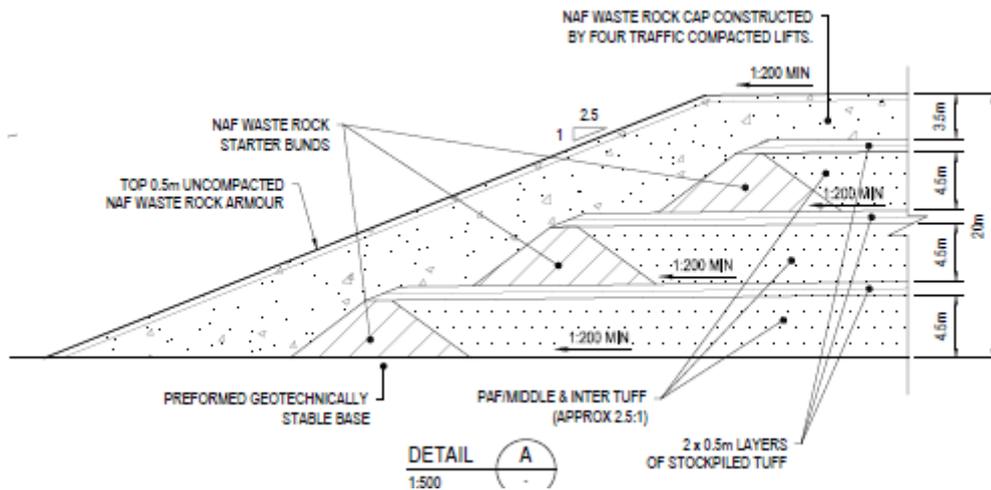


Fig. 4. Example of detailed engineered co disposal where under-slope PAF disposal is required

The co disposal option was preferable over a PAF cell for the following reasons:

- There is flexibility in the disposal of PAF over the life of the WRD as there is not a restricted area in which PAF has to be placed. Rather PAF disposal can be completed in a progressive manner. This is important as PAF was predicted to be produced over the life of the operation.
- Disposal under slopes was required due to site constraints and dump land forming therefore engineered containment was required as infiltration could not be guaranteed to be prevented by a cover system
- There was an availability of NAF Tuff material on site that can be easily compacted into low permeability layers. Tuff material was also likely to be produced progressively over the life of the operation
- Geochemical assessment indicated the Tuff materials may act to reduce AMD discharges as a result of passivation of pyrite oxidation, retardation of metals leaching, and buffering of pH.

The design allowed for co disposal of PAF and NAF Tuff materials together in paddock dumped lifts of 4.5m. In between lifts, traffic-compacted layers of Tuff were to be placed to form horizontal low permeability breaks to oxygen and water ingress.

The design was operationally simple as PAF can be placed at the rate it comes out of the pit. Some areas of the dump may have no PAF as a result of excavation schedule but this does not matter in context as the design does not rely on PAF being placed in specific areas.

6.0 GEOCHEMICAL TESTING OF CO DISPOSAL OPTION

A series of detailed geochemical tests were completed to validate the co disposal option. Two materials were identified as potential co disposal agents:

- NAF Tuff (with no appreciable PAF component)
- NAF BIF with no appreciable PAF component and appreciable acid neutralizing capacity (ANC) as a result of presence of carbonates

The tuff was found in discrete layers and so could more easily be separated and recovered while the BIF was more difficult to recover.

Material that required management included pyritic material with an elevated PAF potential which was found in both BIF and in a Tuff layer. Kinetic net acid generating (NAG) tests indicated that this Tuff material with a similar (net acid producing potential) NAPP to BIF material was not as fast reacting. The chart below shows a kinetic NAG test carried out on:

- PAF Tuff NAPP: 66 H₂SO₄/t
- PAF BIF NAPP: 43 H₂SO₄/t

As can be seen the Tuff sample has slower reaction kinetics than the BIF sample indicating that it may have some buffering/passivation properties.

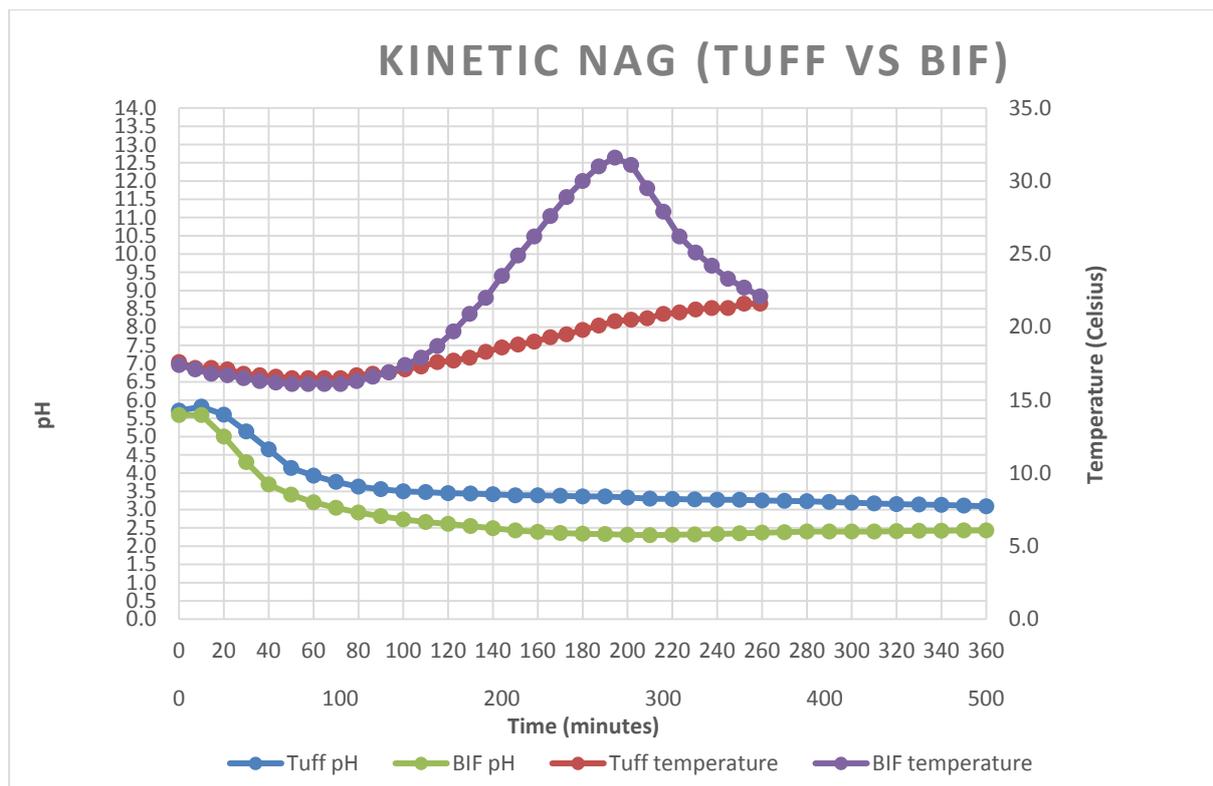


Fig. 5. Results of Kinetic NAG testing

The Tuff was identified from this initial geochemical testing as potentially having the following properties:

- Potential passivation of pyrite oxidation
- Potential retardation of metals leaching
- Potential buffering of acidic pH.

An acid base characterization (curve) ABCC test was carried out to determine the relative properties of the NAF Tuff and NAF BIF:

Table 1. ABCC testing results

Sample ID	ANC	ABCCUnits
	kg H ₂ SO ₄ /t	
Tuff (S1)	1.745	<1
BIF (TP 315606)	18.76	20.00

As can be seen from Table 1 the NAF BIF has all ANC present in an available form, however the NAF Tuff appears to have very limited buffering capacity.

An x ray diffraction (XRD) was carried out on the NAF Tuff to determine its mineralogy which returned major minerals as quartz, illite, kaolinite and muscovite. It is possible that although the material has low buffering capacity to the ABCC test, the clay minerals may offer passivation of AMD reaction and sorption of metals as a result of cation exchange.

To determine the effectiveness of the NAF Tuff and the NAF BIF as co disposal agents a leaching test was carried out which included the following rationale:

- Experiment A: A sample (200g) of PAF material from site with high soluble sulfate minerals was subject to a 24hr 1:1 leach using water (sample 315609). This produced an acidic leachate (200ml) with dissolved metals that was considered to be reflective of leachate that may be generated within the waste rock dump (WRD). The pH of this leachate was 3.3. This pH was constant with the Kinetic NAG test of the pyritic tuff which has an endpoint of pH 3.1 (Figure 5).
- Experiment B: Three samples of PAF material of the pyritic BIF were chosen and subjected to a NAG test. The liquor (200ml) from the NAG test was retained as an example of the leachate that may be generated from the WRD. The pH of these leaches were consistent with the endpoint of the Kinetic NAG test of the pyritic BIF which was pH 2.4 (Figure 5), the results for the NAG tests are shown below:
 - 106223: 2.29
 - 106224: 2.31
 - 315611: 2.71

Results from the experiments below are shown in Figures 6 and 7

- Experiment C: 100ml of the water-leached PAF sample was then mixed with 100g of the NAF Tuff (material was not pulverized, sand to gravel size material used) and left for 24 hrs

- Experiment D: 100ml of the water leached PAF sample was then mixed with 100g of the NAF BIF (material was not pulverized, sand to gravel size material used) and left for 24 hrs
- Experiment E: 100ml of the NAG liquor from PAF sample 106223 was then mixed with 100g of the NAF Tuff (material was not pulverized, sand to gravel size material used) and left for 24 hrs
- Experiment F: 100ml of the NAG liquor from PAF sample 106223 was then mixed with 100g of the NAF BIF (material was not pulverized, sand to gravel size material used) and left for 24 hrs
- Experiment G: 100ml of the NAG liquor from PAF sample 106224 was then mixed with 100g of the NAF BIF (material was not pulverized, sand to gravel size material used) and left for 24 hrs
- Experiment H: 100ml of the NAG liquor from PAF sample 106224 was then mixed with 100g of the NAF Tuff (material was not pulverized, sand to gravel size material used) and left for 24 hrs
- Experiment I: 100ml of the NAG liquor from PAF sample 315611 was then mixed with 100g of the NAF BIF (material was not pulverized, sand to gravel size material used) and left for 24 hrs
- Experiment J: 100ml of the NAG liquor from PAF sample 315611 was then mixed with 100g of the NAF Tuff (material was not pulverized, sand to gravel size material used) and left for 24 hrs

The results from the experiments are shown as follows:

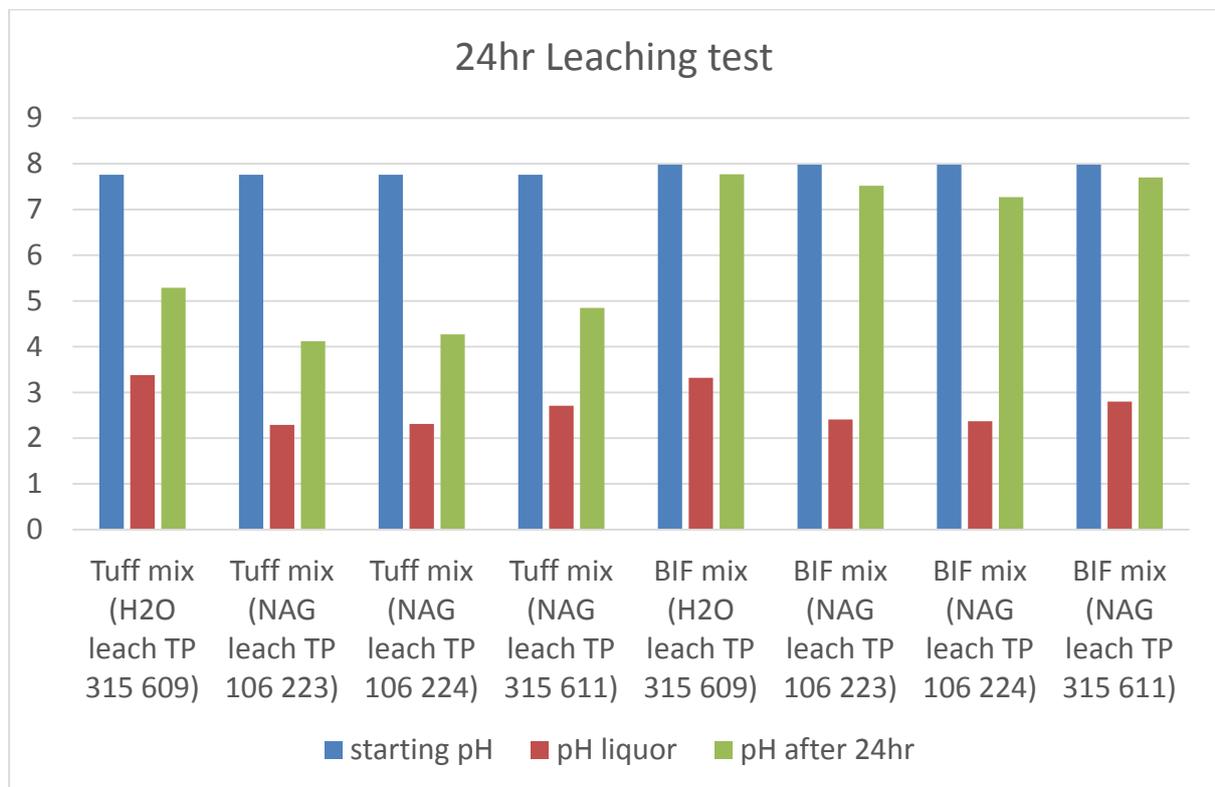


Fig. 6. Results of leach testing of co disposal materials (pH)

Figure 6 shows:

- The NAF Tuff material buffers the acidic pH of all the leachates with the pH raised to between 4-5 from 2-3 after 24 hours. This is still slightly acidic however it is within the range of iron and aluminum precipitation and therefore if replicated on site is likely to reduce AMD impacts.
- The NAF BIF provides a higher degree of buffering than the NAF Tuff, with all results being above pH 7, this would be expected from the ABCC testing which indicated that the material contains readily available buffering capacity.

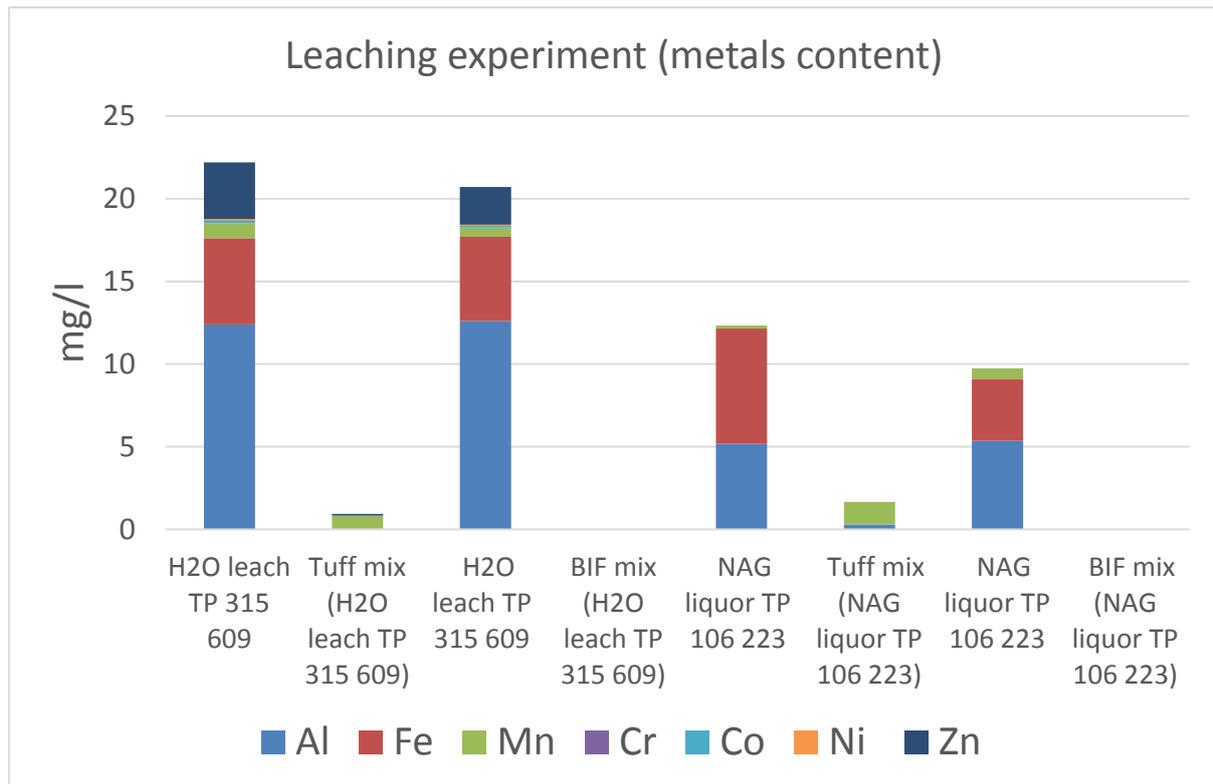


Fig. 7. Results of leach testing of co disposal materials (dissolved metals)

Figure 7 shows the results of the analysis of the liquors from the experiments. The figure shows:

- Both the NAF Tuff and the NAF BIF are very effective in removing dissolved metals from the leachate solution. Aluminum iron and zinc were found in the initial liquor from 315609 at a combined concentration over 20mg/l, these elements were reduced to less than 1mg/l combined after the 24hr leaching test.
- Manganese appears to not be removed from solution by the NAF Tuff, but it is by the NAF BIF. It is likely that this relates to the higher pH achieved by the NAF BIF due to higher buffering capacity.

The results from Figure 6 and 7 are perhaps surprising given that the NAF Tuff from testing had negligible buffering capacity and yet was very effective in both raising the pH of the solution and removing metals from solution. It is likely that cation exchange in the clay

minerals is responsible for the buffering and metal removal seen in the experiments. This property along with the fact that the material can be traffic-compacted into low permeability layers makes the Tuff a very useful co-disposal agent.

On this basis it was determined that the NAF Tuff would be the more suitable co-disposal agent given:

- The NAF Tuff contains clay minerals and when traffic-compacted will form a low permeability layer. The NAF BIF is hard rock and so will not form an effective low permeability layer
- The NAF Tuff appears to perform effectively to both buffer pH and to remove metals from solution
- The NAF Tuff was found in the block model to be constrained to specific geological horizon and is visually identifiable and therefore it was more practical to segregate for use.

7.0 CONCLUSIONS

The use of PAF cells is ubiquitous in the mining industry as a means to provide a convenient management solution for PAF waste. However the concept has fundamental flaws that makes the practice questionable from a mine closure and liability perspective. Co disposal is presented as a feasible alternative that can both be compatible with operations on site and can offer a management solution that has a higher factor of safety than conventional PAF cells.

Detailed geochemical testing has been carried out to demonstrate the effectiveness of co disposal. In addition the testing demonstrates that even materials that appear from basic static tests to have limited use as co disposal agents can in fact possess advantageous geochemical properties. The NAF Tuff material has been demonstrated to possess a number of properties that make it suitable for use as a co disposal agent. This is from a geochemical, physical, planning and operational viewpoint.

The identification of co disposal as an alternative option to the PAF cell on sites is only possible with collaboration and coordination between mine planners, engineers, site geologist, consulting geochemists and regulators, and some lateral thinking. It is only once the paradigm of the “PAF cell as the solution” has been replaced from thinking that progress can be made to improve waste management solutions. For this to happen alternatives have to be presented in a manner that makes logical and financial sense to all of these stakeholders.

8.0 REFERENCES

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