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Assessment Report: Ranger Pit 1 Final Tailings Deposition Level to +7 mRL

K Turner, K Tayler, A Costar, C Zimmermann, M Bouma and P Baker

February 2017

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The Department acknowledges the traditional owners of country throughout Australia and their continuing connection to land, sea and community. We pay our respects to them and their cultures and to their elders both past and present.

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Executive summary

Responsibility for the regulation of uranium mining in the Alligator Rivers Region (ARR) has been delegated by the Commonwealth to the Northern Territory (NT) Minister for Primary Industry and Resources via a series of inter-governmental agreements. The working arrangements between the NT and the Commonwealth require the NT Minister for Primary Industry and Resources to seek the advice of the Supervising Scientist with respect to uranium mining activities in the ARR.

The *Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine* stipulate the Commonwealth's environmental protection conditions for Ranger mine, with which the operator must comply. The mine operator, Energy Resources of Australia Ltd (ERA), is responsible for demonstrating achievement of the Environmental Requirements. The Supervising Scientist plays a key role, along with other stakeholders, in assessing the adequacy and acceptability of the information provided by ERA in doing so.

The Environmental Requirements stipulate that all tailings produced at Ranger mine must be placed in the mine pits for permanent storage, and ERA must demonstrate that for 10,000 years after mine closure tailings will not be exposed; contaminants arising from tailings will not cause environmental impacts in the surrounding Kakadu National Park; and any impacts within the Ranger Project Area are as low as reasonably achievable.

Formal approval for placement of tailings in Pit 1 was initially granted by the NT Government in 1995 and tailings deposition commenced in 1996. In 2005 approval was given to temporarily store tailings to a maximum level of +12 meters Reduced Level (mRL), alleviating the risk (at the time) associated with the high water level in the tailings dam. A condition of the 2005 approval was that further approval would be required, including justification of the final tailings level, prior to the permanent capping and closure of Pit 1. To satisfy this condition, and to demonstrate achievement of the above Environmental Requirements, an application for the approval of the permanent storage of tailings in Pit 1 to a final average tailings level of + 7 mRL, *Pit 1 Notification – Final-in-pit tailings level*, was submitted to stakeholders on 16 March 2016 by ERA.

The Supervising Scientist undertook a comprehensive review and assessment of the Application, including seeking technical advice from a range of independent experts and hosting a multi-day, widely attended workshop. Subject to the proposed conditions detailed in Section 3.2, the Supervising Scientist supports approval of an average final tailings level of +7 mRL in Pit 1 and the commencement of the bulk backfill activities, which will improve consolidation of tailings and maximise the recovery of tailings pore water during the operational phase whilst it can be actively treated.

While the approach proposed by ERA for the long-term storage of tailings in Pit 1 was considered to be acceptable, looking at Pit 1 in isolation does not enable a thorough assessment of the potential environmental impacts from the rehabilitated Ranger site as a whole. Therefore, the Supervising Scientist's assessment focused on the risk associated with a maximum average tailings level in Pit 1 of +7 mRL relative to the cumulative risk associated with the whole rehabilitated mine site. The information presented in the Application was sufficient to demonstrate that the risk to Kakadu National Park specifically from tailings stored in Pit 1 is low compared to the cumulative risk associated with the whole rehabilitated mine site and that transfer of tailings to Pit 3 (the only alternative storage location) in order to reduce the final tailings level in Pit 1 would not further reduce this risk.

Cumulative risk needs to be considered with a whole-of-site focus in order to fully understand the potential environmental impacts from the whole rehabilitated mine site. The proposed conditions in Section 3.2 include additional whole-of-site investigations and modelling that will enable a more comprehensive, whole-of-site environmental impact assessment. This assessment will be required for ERA to demonstrate their ability to achieve the Environmental Requirements. The proposed conditions also ensure that ERA implement a comprehensive monitoring program for detecting groundwater seepage around Pit 1, and that clear contingencies are planned and available for implantation if mitigation measures are required in the future.

1 Introduction

1.1 Regulatory Arrangements

The Commonwealth's environmental protection conditions for Ranger mine, with which the operator must comply, are set out in the *Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine* (the Environmental Requirements). The Environmental Requirements are given force through attachment to the *Atomic Energy Act 1953* s41 Authority for ERA to mine uranium within the Ranger Project Area and are reflected in the NT Mining Management Act Authorisation under which Ranger operates.

Clause 2 of the Environmental Requirements pertaining to rehabilitation states:

> *2.1 Subject to subclauses 2.2 and 2.3, the company must rehabilitate the Ranger Project Area to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park*
>
> *2.2 The major objectives of rehabilitation are:*
>
> *(a) revegetation of the disturbed sites of the Ranger Project Area using local native plant species similar in density and abundance to those existing in adjacent areas of Kakadu National Park, to form an ecosystem the long term viability of which would not require a maintenance regime significantly different from that appropriate to adjacent areas of the park;*
> *(b) stable radiological conditions on areas impacted by mining so that, the health risk to members of the public, including traditional owners, is as low as reasonably achievable; members of the public do not receive a radiation dose which exceeds applicable limits recommended by the most recently published and relevant Australian standards, codes of practice, and guidelines; and there is a minimum of restrictions on the use of the area;*
> *(c) erosion characteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas.*
>
> *2.3 Where all the major stakeholders agree, a facility connected with Ranger may remain in the Ranger Project Area following the termination of the Authority, provided that adequate provision is made for eventual rehabilitation of the affected area consistent with principles for rehabilitation set out in subclauses 2.1, 2.2 and 3.1.*

Clause 11 of the Environmental Requirements pertaining to tailings disposal states:

> *11.1 During mining operations and prior to final placement, covering and rehabilitation of the tailings, tailings must be securely contained in a manner approved by the Supervising Authority or the Minister with the advice of the Supervising Scientist which prevents detrimental environmental impact.*
>
> *11.2 By the end of operations all tailings must be placed in the mined out pits.*

11.3 *Final disposal of tailings shall be undertaken to the satisfaction of the Minister with the advice of the Supervising Scientist on the basis of best available modelling, in such a way to ensure that:*

i. the tailings are physically isolated from the environment for at least 10,000 years;
ii. any contaminants arising from the tailings will not result in any detrimental environmental impact for at least 10,000 years;
iii. radiation doses to members of the public will comply with relevant Australian law and be less than limits recommended by the most recently published and relevant Australian standards, codes of practice and guidelines effective at the time of the final disposal.

Whilst the Supervising Scientist oversees ERAs compliance with the Environmental Requirements generally, clauses 2.1, 11.1 and 11.3 specifically require the Supervising Scientist to provide advice to the Minister for Resources and Northern Australia in relation to mine rehabilitation and the final disposal of tailings. This report forms the Supervising Scientist's advice to the Minister for Resources and Northern Australia, and the NT Minister for Primary Industry and Resources, with respect to the final disposal of tailings in Pit 1.

1.2 Pit 1 Overview

Ranger Pit 1 is located within the Corridor Creek catchment. Corridor Creek drains surface water and shallow groundwater to Magela Creek, via Georgetown Billabong.

Pit 1 is a conventional open cut pit that was mined between May 1980 and December 1994. The excavated surface area is 42 ha, with a surface diameter of approximately 700 m and a final depth of 170 m below the surrounding land surface. Tailings were deposited into the pit from August 1996 and reached the maximum permitted (average) level of +12 mRL in December 2008.

Modelling has demonstrated that the tailings will consolidate up until the end of 2018 and that the final average tailings level will be +7 mRL (minimum elevation less than +1 mRL in the centre to a maximum elevation of +15 mRL at the pit edges) (ATC Williams, 2012). Final consolidation is dependent on the timing of load placements, including the bulk waste rock backfill that will be placed over the tailings.

1.3 Previous Applications

Previous regulatory approvals for the deposition of tailings in Pit 1 are summarised below.

Deposition of Neutralised Tailings in Ranger #1 Pit - 1995

The original application for the use of Pit 1 as a repository for tailings was submitted by ERA on 3 August 1995 and was subsequently approved on 5 September 1995 (ERA, 1995). The Application was titled *Deposition of Neutralised Tailings in Ranger #1 Pit* and sought approval to deposit and store tailings to a level of 0 mRL with a target density of 1.2 – 1.3 t/m^3. The Application indicates that seepage at depth is unlikely due to the low permeabilities of the deeper aquifers. Most seepage outflow from the pit 'would be concentrated in the Hanging Wall Series rocks at and above bench 0 (0 mRL) in the south-east corner of the pit. Consequently, if tailings are deposited above bench 0 (0 mRL), there would be potential for tailings seepage to reach surface water in a direction generally east of the pit.' Notably, dry season seepage inflow rates from the Hanging Wall Sequence were estimated, based on dewatering rates from Mine Bore L (MBL) to range between 3.3 L/s to 5.5 L/s.

Interim Deposition of Tailings to RL+12 in Ranger #1 Pit - 2005

An extension of the original 1995 Application was submitted by ERA on 11 May 2005, entitled *Interim Deposition of Tailings to RL+12 in Ranger #1 Pit* (ERA, 2005). This Application outlined an interim operational tailings management strategy that involved temporary storage of tailings to a level of +12 mRL. This would allow ERA to field-test the security of in-pit tailings storage and to maximise the volume of tailings in Pit 1. At the time of submission of this Application, the final level of tailings in Pit 1 and strategies for pit decommissioning and rehabilitation had yet to be determined. The Application was intended to cover the period of mine operations until Pit 3 had been prepared and approved for tailings deposition, thereby reducing the requirement to recommission the tailings dam which had reached its maximum level. To reduce the risk of seepage into the permeable zone above 0 mRL, a seepage limiting barrier was constructed in the south-eastern part of Pit 1, which extended from 0 mRL to +15 mRL. A comprehensive monitoring system was installed to enable detection of seepage from the pit and a number of contingency measures were developed for implementation should this occur. These contingencies formed part of the conditions of approval, granted on 6 August 2005:

> *The measures that have been designed to correct any significant excursion of seepage from the pit include:*
>
> 1 *treatment and disposal of process water to lower the level of water in the pit;*
> 2 *creating an hydraulic barrier to seepage by raising groundwater levels behind the pit wall, for example by stopping pumping at the MB-L dewatering bore;*
> 3 *additional grouting;*
> 4 *implementing a seepage recovery system;*
> 5 *modifying the properties of tailings to reduce the permeability of tailings deposited against the barrier and pit walls;*
> 6 *modifying the existing barrier or installing an additional seepage-limiting barrier (for example, a slurry wall);*
> 7 *interim deposition of tailings in the tailings dam; and*
> 8 *transfer of tailings out of the pit to a level where seepage is minimised.*

The conditions of approval of the 2005 Application, which remain in force, are as follows:

> *ERA is authorised to store tailings to an average level of RL+12 and process water to RL+14 in Ranger Pit #1 in accordance with the Application titled* Interim Deposition of Tailings to RL +12 in Ranger #1 Pit *date 11 May 2005 (the Application) subject to the following conditions:*
>
> 1.1 *The Supervising Authority may direct ERA to either implement any, or all, of the contingencies detailed under Section 3.8 of the Application or to remove tailings and process water to a scientifically justifiable level.*

1.2 *Prior to the permanent storage of tailings in Ranger #1 Pit ERA is required to submit a further Application for the permanent storage of tailings in the Pit #1, including appropriate supporting information, for consideration by the Supervising Authority.*

1.3 *ERA will monitor potential groundwater impacts resulting from the storage of tailings in Ranger #1 Pit in accordance with section 3.7 of the Application and make all resulting data available to the Supervising Authority as soon as is practicable after the verified data are available.*

1.4 *In the event that an impact from the storage of tailings in Ranger #1 Pit is determined ERA will implement contingency actions in accordance with section 3.8 of the Application.*

1.5 *Any alteration to the monitoring program or contingency actions contained in the Application must have the approval of the Supervising Authority.*

Section 3.3.2 of the 2005 Application indicated that 'downstream groundwater interception bores' were a feasible option for minimising and managing seepage from Pit 1.

These conditions remain in force until the current Application is approved.

2 Assessment Overview

2.1 Application Summary

Condition 1.2 of the 2005 approval for interim storage of tailings in Pit 1 was that ERA would, prior to the permanent storage of tailings in Pit 1, submit a further Application for consideration and approval by the Supervising Authority, including a final maximum tailings level in Pit 1, along with appropriate supporting information to demonstrate this maximum level minimises potential environmental harm. The application *Pit 1 Notification – Final-in-pit tailings level*, dated 16 March 2016, was submitted to satisfy this condition and is the subject of this assessment report (ERA, 2016).

The 2016 Application for a final tailings level in Pit 1 includes information related to:

- the Pit 1 closure strategy
- a best practicable technology assessment
- an environmental risk assessment
- potential impacts related to identified risks
- future monitoring requirements.

In particular, the Application includes information on a numerical groundwater contaminant transport model that describes transport of contaminants of potential concern (COPCs) in groundwater from the pit to the surrounding environment. The model simulates groundwater flow and non-reactive transport of contaminants to enable estimation of contaminant loads delivered from Pit 1 sources (tailings and waste rock) to Corridor Creek for 10,000 years after closure, in accordance with the Environmental Requirements.

Various other models are also referenced, including a tailings consolidation model, a landform evolution model, a stockpile resource model, the Ranger groundwater conceptual model and the method used to predict concentrations of radon decay products.

2.2 Assessment Process

A review and assessment of the Application was conducted by the Supervising Scientist Branch of the Department of the Environment and Energy's Science Division (Appendix 2). The Office of Water Science Branch of the Department of the Environment and Energy's Science Division provided advice on the general hydrogeological aspects of the Application (Appendix 3). In addition to this, external expertise was sought to undertake independent technical reviews of the tailings consolidation strategy and modelling, the groundwater and contaminant transport modelling and the source term geochemistry. Hydrogeologic Pty Ltd, the South Australian (SA) Department of Environment, Water and Natural Resources (DEWNR) and DR Jones Environmental Excellence were engaged to undertake these reviews and their reports are presented in Appendices 4, 5 and 6, respectively.

The tailings consolidation review focuses specifically on Pit 1 whereas the groundwater modelling and the source term geochemistry reviews have more of a whole-of-site focus. As a result, a number of issues raised by the reviewers were not considered to be directly relevant to assessing the appropriateness of +7 mRL as a final maximum average tailings level. These concerns have been acknowledged in this report as key knowledge gaps that will need to be investigated further to determine potential whole-of-site impacts on the environment. The review findings are summarised in this report.

A groundwater workshop was held by SSB on 5–7 September 2016 to discuss the Pit 1 groundwater and contaminant transport modelling along with the broader Ranger hydrogeological system, as represented in the Ranger Conceptual Model (INTERA, 2016). Participating stakeholders included ERA, the Gundjeihmi Aboriginal Corporation (the representative body of the Mirrarr Aboriginal people), the Northern Land Council, the Office of Water Science, Geoscience Australia, NT DPIR, SA DEWNR, DR Jones Environmental Excellence and staff from the Supervising Scientist Branch. The outcomes of the workshop are summarised in Appendix 7 and have informed this assessment report.

2.3 Key Environmental Risks

2.1.1 Groundwater

A key risk to the environment associated with permanent disposal of tailings in Pit 1 is from contaminants transported via groundwater seepage to surrounding surface water bodies, both on and off the Ranger Project Area. The key components that govern the transport of contaminants from Pit 1 are outlined below, along with the key findings from the reviews as they relate to each component.

2.1.1.1 Source Term Geochemistry

DR Jones Environmental Excellence conducted an independent review of the source term characterisation for tailings, pit tailings flux, waste rock and groundwater in, and surrounding Pit 1. In the context of this report, a source term is considered to be an estimate of the concentration of a contaminant that is potentially available for transport into the receiving environment from a specific source over a certain period of time. The review covered geochemical processes and associated assumptions made in the contaminant transport modelling undertaken by ERA. While the review extends to broader site-wide issues, a number of recommendations apply to this Application and the assessment of the final tailings level in Pit 1.

Importantly, the review found that the list of COPCs identified was appropriate and that the overall approach of assuming non-reactive transport to estimate loads of contaminants discharged from Pit 1 through time was adequate. However, the reviewer recommended that calcium should be included in the model and that further consideration should be given to the anticipated magnesium/calcium ratio of Pit 1 discharges to ensure a better understanding of potential magnesium toxicity in receiving surface waters.

The review indicated that the modelled annual contaminant loads delivered to Corridor Creek from Pit 1 may be underestimated due to uncertainty in the source term characterisation. In relation to the final tailings level in Pit 1, this is not considered to be of concern as the contaminant loads predicted to be delivered to Corridor Creek from Pit 1 tailings are significantly lower than the loads currently reporting to the creeks during mine operations. Further to this, the data presented in the Ranger Conceptual Model indicates that that most significant source of contaminants on the rehabilitated mine site is waste rock, and that the peak annual magnesium load from Pit 1 tailings is equivalent to approximately 1.5% of the peak annual magnesium load that is expected to be generated from the waste rock landform. While further refinement of the source terms will improve confidence in the overall site-wide contaminant loading estimates, any changes to the current load estimates for Pit 1 would be negligible compared to other contaminant sources.

The Supervising Scientist agrees with the recommendation to include calcium in the contaminant transport modelling and to improve the general characterisation of the key sources terms. Both of these recommendations have been included in the proposed conditions for approval (Section 3.2).

2.1.1.2 Tailings Consolidation Modelling

The tailings consolidation model estimates the volume of tailings pore water that will be expressed from Pit 1 during the consolidation process, as the tailings settle underneath the load of waste rock above to a final average level of +7 mRL. The pore water expressed from the Pit requires active management and treatment prior to release, which is only possible up to 2025 after which time the water treatment facilities on site will be decommissioned. Any remaining pore will become a long-term source of contaminants (pit tailings flux) and maximising its removal whilst it can be treated is critical to reduce future potential environmental effects.

Modelling indicates that the majority of consolidation, and hence expression of pore water, will occur during the placement of the initial 20 MT of waste rock bulk backfill. The model predicts that if bulk backfill commenced in August 2016, the peak in pore water expression will occur during 2018, at around 300 m^3 per day. The model estimates that 'minimal' volumes are likely to be expressed beyond 2026. The consolidation model was reviewed by Hydrogeologic Pty Ltd on behalf of SSB. Despite concern about the model uncertainly the review indicated that the model was 'generally fit for purpose' for estimating the final level of tailings after consolidation and the associated pore water volumes expressed during consolidation. The model demonstrated adequate performance as predicted settlement values corresponded well with actual settlement values measured between 2013 and 2015. However, the review recommended that ongoing settlement monitoring was necessary to allow further verification and to improve quantification of model uncertainty. The Supervising Scientist agrees with this recommendation and has included it in the proposed approval conditions (Section 3.2).

A further concern raised in the review was that the tailings consolidation model did not include sufficient data to represent the existing water balance for Pit 1. A water balance defines the water flowing in and out of the pit and should include measurements of rainfall, groundwater inflows, evapotranspiration and expressed pore water. The review considered that a water balance is required to improve the accuracy of flow estimates over time and that the lack of an adequate water balance results in significant uncertainty in the current modelled flow predictions. The review recommended that water balance measurements should be collected to improve confidence in the consolidation model capability. The Supervising Scientist agrees with this recommendation and has included it in the proposed approval conditions (Section 3.2).

2.1.1.3 Contaminant Transport Modelling

The movement of contaminants in groundwater away from Pit 1 was simulated using a groundwater numerical model. This model was reviewed formally by SA DEWNR and was also scrutinised at a groundwater workshop which was attended by various experts as well as ERA and the model developers.

It was generally considered that the model is suitable for the intended purpose of estimating average and peak annual contaminant loads delivered to Corridor Creek over 10,000 years. The predicted contaminant contribution from tailings within Pit 1 is low relative to the contribution currently delivered to Corridor Creek during mine operations, which has not resulted in any observed environmental impacts. A key criticism of the model was the short calibration period (1 year) compared to the extreme length of the predictive period (10,000 years). However, while model calibration to a longer and/or wider dataset may increase the accuracy of the predicted timing of peak contaminant delivery to Corridor Creek, it would be unlikely to increase the magnitude of the peak contaminant load, which is more important for determining environmental impact.

The review found that the overall model uncertainly was high, resulting in low confidence in the modelled results. The low confidence was mainly due to:

- The short calibration period (1 year) compared to the extreme length of the predictive period (10,000 years), as indicated above.
- Uncertainty in the assumed initial conditions for the model, specifically with respect to groundwater levels (which are assumed to return to pre-mining levels by 2025) and groundwater quality (which is assumed to represent background quality).
- Insufficient sensitivity and uncertainty analysis for parameters that may govern the migration of contaminants, including porosity and hydraulic conductivity.

The geochemical review undertaken DR Jones Environmental Excellence also identified the above issues and the associated recommendations have been included in the proposed approval conditions (Section 3.2).

The groundwater modelling will need to integrate with surface water models to allow the estimation of contaminant concentrations in surface water. Historical stream water quality monitoring data have shown that shallow groundwater in the Corridor Creek catchment expresses into the creek channel under low surface flow conditions, particularly towards the end of the wet season. As a result, contaminants transported from Pit 1 in the shallow groundwater are likely to enter the creek channel primarily during periods of recessional flow. To be able to estimate the contaminant concentrations during these low flow periods, the groundwater contaminant transport model would need to produce outputs at a higher temporal resolution. Both reviews agree that further work is required to enable the estimation of loads at a spatial and temporal resolution more appropriate for estimating contaminant concentrations in Corridor Creek over the seasonal flow cycle. Improving the model resolution is necessary to inform the future assessment of whole-of-site surface water impacts.

The need for undertaking higher resolution modelling to assess impacts arising from contaminant toxicity on a whole-of-site basis is included in the proposed approval conditions (3.2).

Further to the findings outlined above, the Pit 1 groundwater and surface water monitoring plan included in the Application was deficient. Given the overall model uncertainty there is a need for ongoing monitoring to enhance the hydrogeological conceptualisation and improve model calibration. The current monitoring proposal does not indicate how these issues will be addressed and may be inadequate for detection of seepage from the pit. Some of the proposed monitoring bores have screen lengths intersecting multiple aquifers which will confound the water level and water quality data. In order to enable implementation of future mitigation measures, if required, an ongoing understanding of groundwater movement and quality is needed. To achieve this, a more substantial groundwater monitoring program is necessary. Associated recommendations have been included in the proposed approval conditions (Section 2.3).

2.1.1.4 Groundwater/Surface Water Interactions and Stream Flow

Understanding groundwater/surface water interactions is important for the conversion of predicted annual contaminant loads to concentrations that can be used to assess toxicological impacts in surface waters. Further work is required to define these interactions to enable a better understanding of the locations and rates of delivery of contaminants from Pit 1, and more broadly across the mine site, to the surrounding surface waters. In the case of Pit 1, modelling is required to characterise the surface water flow dynamics in Corridor Creek post-rehabilitation, after the removal of several small dams and the cessation of treated mine water inputs.

The Application included an estimate of the stream-flow rate that would be required in Corridor Creek (1 m^3 second) to effectively dilute contaminant concentrations to environmentally acceptable levels. This estimate assumes that the groundwater enters the creek at a constant rate throughout each year, which is not the case and oversimplifies the dynamic interactions between groundwater and surface water. This is a critical knowledge gap that reduces the overall confidence in the Ranger mine hydrogeological conceptualisation as well as current and future predictive modelling. Associated recommendations have been included in the proposed approval conditions (Section 3.2).

The contaminants arising from tailings in Pit 1 will report to Corridor Creek, however as discussed above, the possible environmental impacts from tailings in Pit 1 need to be considered in the context of the entire rehabilitated mine site. This includes any existing groundwater contamination, the tailings stored in Pit 3 and the final landform itself. The peak annual contaminant loads estimated to be delivered to Corridor Creek from Pit 1 were small in comparison to the loads estimated for other contaminant sources. This suggests that impacts to the surrounding Kakadu National Park arising specifically from tailings in Pit 1 are highly unlikely, and would not be meaningfully reduced by a reduction in tailings level.

2.1.2 Landform

To demonstrate achievement of a number of the rehabilitation Environmental Requirements, the final landform design must demonstrate that gully formation will not result in the exposure of tailings, and that the landform will support and sustain plant growth. The final landform design is still undergoing assessment and has not yet been approved.

The landform evolution modelling presented in the Application shows the formation of a gully over the southern portion of Pit 1, reducing the depth of the waste rock cap above the tailings from approximately 15 meters to 5 meters. The error associated with this distance is likely to be ± 10 m because the digital elevation model used to represent the landform surface in the landform evolution modelling had a vertical resolution of approximately 10 metres. This suggests that the gully shown in the Application could possibly lead to exposure of tailings in the long term. In relation to Pit 1 (and eventually Pit 3), the final landform design should be revised to minimise gully formation over tailings and will not be endorsed until the Supervising Scientist is satisfied that the risk of tailings exposure within 10,000 years in minimised. Related recommendations have been included in the proposed approval conditions (Section 3.2).

The Application includes a schedule of works for the rehabilitation and closure of Pit 1, indicating that revegetation of the Pit 1 waste rock cap will commence 12 months after the commencement of the bulk backfill process. Prior to completion of the bulk backfill and commencement of vegetation, the final landform design must be approved. Additional information relating to the ability of the waste rock cap on Pit 1 to support and sustain plant growth (such as plant available water) is required before the design can be approved. Related recommendations have been included in the proposed approval conditions (Section 3.2).

The final tailings level in Pit 1, and the placement of the initial layer of bulk backfill, does not impact on the ability to further revise the final landform surface or the design of a plant growth medium. Therefore the need to complete this additional work should not prevent approval of the final tailings level and the commencement of the initial stage of bulk backfill. However, the Application contained very little information on the bulk backfill strategy, such as the methods and timing of rock placement. This should be provided before bulk backfill commences. Associated recommendations have been included in the proposed approval conditions (Section 3.2).

2.1.3 Radiation

Exposure to radiation from the tailings permanently stored in Pit 1 can occur via three pathways: inhalation of radon decay products; ingestion of radionuclides in food, dust and water; and external exposure to gamma radiation. According to Environmental Requirement 11.3 the total radiation dose to members of the public from all pathways must not exceed applicable limits, and land use restrictions required to ensure this must be kept to a minimum. The most current limit applicable to mining in Australia is 1mSv per year, which excludes the dose received from natural and medical sources (ARPANSA, 2005).

The Application addressed each of the three exposure pathways and concluded that, provided tailings are not exposed due to erosional process, radiation exposure from tailings will be negligible. The Supervising Scientist agrees that the majority of the total radiation dose from the rehabilitated mine site will come from the waste rock landform, with a negligible contribution from the buried tailings.

2.1.3.1 Inhalation pathway

The risk of radiation exposure from the inhalation of radon decay products from tailings is considered to be negligible because the proposed depth of the waste rock cap will significantly reduce the emanation of radon. The Supervising Scientist is satisfied that a reduction in tailings level in Pit 1 will not meaningfully reduce radon emanation rates.

Landform modelling indicates there is a possibility that gullies may form above Pit 1. This would reduce the waste rock depth above the stored tailings and result in an increase in radon emanation rate in the immediate vicinity of the gully. Given the localised nature of the increased risk, it is not considered to significantly increase the overall risk of radiation exposure from radon decay products from the tailings source.

2.1.3.2 Ingestion pathway

Radiation exposure to people via the ingestion pathway occurs when radionuclides in dust, bushfoods or water are ingested. Ingestion of radionuclides from tailings dust is not possible unless tailings are exposed, so the main risk to people is from ingesting contaminated bushfoods, such as mussels and native fruits and from the contamination of surface water.

In the absence of exposed tailings, the primary mechanism for tailings derived radionuclides to enter the surrounding environment is via groundwater seepage into surrounding surface waters. Key radionuclides, radium and polonium, were included in the groundwater contaminant transport modelling discussed in Section 2.3.1.3. The average annual loads of radium and polonium predicted to seep from tailings in Pit 1 into surrounding surface waters were low compared to the loads currently released during mine operations, and compared to the annual load limits for these radionuclides in surface waters. An extensive monitoring data set has shown that operational radionuclide loads have not been of human health significance. Accordingly, radiation dose to the public from Pit 1 tailings via the ingestion pathway is not of significance.

The Application suggests that the depth of the waste rock cap is sufficient to prevent any interaction between tailings and the roots of plants growing on the surface, however this is not well supported. The Supervising Scientist considers that further work is required to validate this and has included associated recommendations in the proposed conditions for approval (Section 3.2).

2.1.3.3 External pathway

Radiation exposure via the external gamma pathway can only occur in the immediate vicinity of exposed tailings. Provided they are not exposed, tailings in Pit 1 should not provide any external gamma dose to humans.

3 Assessment Outcomes

2.4 Summary

The Supervising Scientist has undertaken a detailed review and assessment of the 2016 application, *Pit 1 Notification – Final-in-pit tailings level*, including the tailings consolidation modelling and the numerical groundwater modelling, both used to estimate loads of contaminants reporting to Corridor Creek over time.

Subject to specific proposed approval conditions outlined in Section 3.2, the Supervising Scientist supports approval of a final average tailings level of +7 mRL in Pit 1 and the commencement of the bulk backfill activities, which will improve consolidation of tailings and maximise the recovery of tailings pore water during the operational phase whilst it can be actively treated.

The level of tailings currently contained in Pit 1 could only be reduced by transferring tailings to Pit 3. A reduction in the final tailings level in Pit 1 from the proposed average level of +7 mRL to 0 mRL (an historically acceptable level) would reduce the total tailings volume in the pit by approximately 8%, representing a negligible reduction in the tailings contaminant source. This is unlikely to reduce the risk to the environment. Furthermore, elevating the final tailings level in Pit 3 may increase the risk to the environment by resulting in:

- increased risk of tailings exposure should the Djalkmara watercourse re-form near its original location, which would reduce the cover between the tailings and the surface of the landform
- increased risk of contaminants entering Magela Creek through zones of comparatively high permeability, including the 'Djalkmara Sands' zone located to the north-east of Pit 3 and the fault-zone, located to the north of Pit 3
- decreased opportunity for dilution of contaminants prior to surface waters flowing into the surrounding Kakadu National Park, as Pit 3 is located about 100 m from Magela Creek (whereas Pit 1 is located adjacent to Corridor Creek, a minor tributary that flows into Magela Creek via Georgetown Billabong thus offering significant opportunity for dilution).

The Application and the Ranger Conceptual Model (INTERA, 2016) provided sufficient information to conclude that the risk to Kakadu National Park specifically from the tailings in Pit 1 is low compared to the cumulative risk associated with the whole rehabilitated mine site, and unlikely to impact human health or the environment.

Cumulative risk needs to be considered with a whole-of-site focus in order to fully understand the potential environmental impacts from the whole rehabilitated mine site. The proposed conditions in Section 3.2 include additional whole-of-site investigations and modelling that will enable a more comprehensive, whole-of-site environmental impact assessment. This assessment will be required for ERA to demonstrate their ability to achieve the Environmental Requirements. While these proposed approval conditions are specific to Pit 1, ERA should consider the cumulative risk to the environment from the whole mine site in their implementation.

2.5 Recommended approval conditions

Based on the best available modelling the Supervising Scientist supports the approval of a final average tailings level of +7 mRL in Pit 1 of the Ranger uranium mine, subject to the following conditions:

1. **Bulk backfill.** Prior to the commencement of any further Pit 1 backfill works ERA must provide a detailed Pit 1 backfill plan for the approval of the Director with the advice of the Supervising Scientist. The plan must demonstrate how the work will reconcile assumptions made in the tailings consolidation model and should include a detailed method and schedule for fill placement, and a comprehensive monitoring program for tailings consolidation, including settlement surveys and water balance measurements.
2. **Landform design.** Prior to commencing the placement of the final six million tons of backfill in Pit 1 ERA must have obtained approval for the final landform design from the Director with the advice of the Supervising Scientist. The design must specifically address issues including plant available water, the potential for plant root interactions with tailings and the formation of gullies over the top of tailings.
3. Within eight weeks of the release of this report ERA should propose a schedule for completion of each of the following for the approval of the Director with the advice of the Supervising Scientist*:*
    a. **Risk assessment.** A revised environmental risk assessment that clearly indicates how each risk was identified, how each risk scenario was evaluated, and how the risk ratings and related management classes were assigned. The assessment must clearly describe each of the existing and proposed controls, including demonstrating how effectiveness and manageability of each control was ranked.
    b. **Geochemistry.** A reactive-transport model for calcium in groundwater and further characterisation of source terms in and around Pit 1, including saturated waste rock, pit tailings flux and groundwater surrounding Pit 1.
    c. **Tailings consolidation.** A plan that outlines an approach to ongoing verification of the tailings consolidation model, which should enable refinement of the pit tailings flux source term for contaminant transport modelling as well as an ongoing understanding of how the groundwater system will respond throughout the bulk backfill process. The plan must include a detailed evaluation of model uncertainty, a monitoring program for settlement plates in Pit 1 and a monitoring program that enables better understanding of the Pit 1 water balance (including measurement of the quantity and conductivity of decant water removed from the pit).
    d. **Groundwater modelling.** Additional groundwater modelling to better estimate the timing and magnitude of contaminant delivery to Corridor Creek throughout the seasonal stream-flow cycle and to better understand the initial period of groundwater stabilisation. Groundwater modelling must be conducted in consideration of groundwater/surface water interactions to allow integration with surface water modelling. Further investigation should be carried out on specific hydrogeological zones that represent potential pathways (e.g. the 'MBL zone' and the Lower Mine Sequence carbonate zone between Pit 1 and Pit 3).
    e. **Surface water modelling.** Additional surface water modelling for the Ranger site and surrounds, including the Corridor and Magela Creek systems,

to estimate post-closure surface water flows and associated concentrations of contaminants in surface waters at a resolution suitable for aquatic toxicity assessment. Surface water modelling must be conducted in consideration of groundwater/surface water interactions to allow integration with groundwater modelling.

f. **Groundwater monitoring.** A groundwater monitoring program appropriate for further refinement of the Ranger hydrogeological conceptualisation, ongoing model validation and early detection of seepage from Pit 1. The program must include a schedule for the routine measurement of groundwater levels, quality and gradients at key locations along with trigger values that can be used to identify seepage from the pit and provide the basis on which to consider implementing contingency measures. Where these locations differ to those in the current Pit 1 monitoring program, as approved in 2005, justification must be provided.

g. **Contingency planning**. A contingency plan that explicitly details all controls that are currently in place to reduce environmental risk, and any planned contingency measures that can be implemented to mitigate impacts in the event that monitoring detects concentrations of contaminants in groundwater that are in excess of those predicted or are likely to be of environmental significance.

4 References

ARPANSA 2005. *Code of Practice on Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing*. Australian Radiation Protection and Nuclear Safety Agency.

ATC Williams 2012. *Pit #1 Updated Consolidation Analysis*. Prepared by ACT Williams on behalf of Energy Resources of Australia Ltd, December.

ERA 2016. *Pit 1 Notification: Final in-pit tailings level*. Energy Resources of Australia Ltd, March.

ERA 2005. *Application to Supervising Authorities: Interim Deposition of Tailings to RL+12 in Ranger #1 Pit*. Energy Resources of Australia Ltd, May.

ERA 1995. *Application for Approval: Deposition of Neutralised Tailings in Ranger #1 Pit*. Energy Resources of Australia Ltd, August.

INTERA 2016. *Final Report: Conceptual model for Ranger Mine*. Prepared by INTERA on behalf of Energy Resources Australia Ltd, July.

Appendix 1

Advice on *Pit 1 Notification: final in-pit tailings level* from the Supervising Scientist to the Northern Territory Minister for Primary Industry and Resources

Australian Government
Department of the Environment and Energy
Supervising Scientist

31 January 2017

Mr Peter Waggitt
Director of Mining Compliance
Department of Primary Industry and Resources
GPO Box 4550
Darwin NT 0801

Dear Mr Waggitt

Re: Pit 1 Notification – final in-pit tailings level

The *Environmental Requirements of the Commonwealth of Australia for the Operation of Ranger Uranium Mine* stipulate the Commonwealth's environmental protection conditions for the Ranger uranium mine, with which the operator, Energy Resources of Australia Ltd (ERA), must comply. In relation to mine site rehabilitation, the requirements specify that all tailings produced at Ranger mine must be placed in the mine pits for permanent storage, and that for 10,000 years after mine closure, tailings must not be exposed and contaminants arising from tailings must not cause environmental impacts in the surrounding Kakadu National Park.

In 2005 interim approval was given to temporarily store tailings to a maximum level of +12 meters Reduced Level (mRL) in Pit 1. A condition of the 2005 approval was that further approval would be required, including justification of the final tailings level, prior to the permanent capping and closure of Pit 1. To satisfy this condition, and to demonstrate achievement of the above Environmental Requirements, an application for the approval of the permanent storage of tailings in Pit 1 to a final average tailings level of + 7 mRL, *Pit 1 Notification – Final-in-pit tailings level*, was submitted to stakeholders on 16 March 2016 by ERA.

The Supervising Scientist Branch has undertaken a detailed assessment of the Application, seeking independent technical advice on groundwater solute transport modelling, tailings consolidation modelling and source term geochemistry. The Branch hosted a groundwater workshop on 5–7 September 2016 where issues identified by the Branch and the independent experts were discussed with ERA and other key stakeholders. The assessment findings, taking into account the workshop outcomes, are summarised in an assessment report, which is provided for your information at Attachment A.

Subject to the recommended approval conditions outlined in Section 3.2 of the assessment report, the Supervising Scientist supports approval of a final tailings level of +7 mRL in Pit 1 and the commencement of the bulk backfill activities.

The information presented in the Application was sufficient to demonstrate that the risk to Kakadu National Park specifically from tailings stored in Pit 1 is low compared to the cumulative risk associated with the whole rehabilitated mine site. Transfer of tailings to Pit 3 (the only alternative storage location) in order to reduce the final tailings level in Pit 1 would not further reduce this risk.

Cumulative risk needs to be considered with a whole-of-site focus in order to fully understand the potential environmental impacts from the whole rehabilitated mine site. The proposed approval conditions include additional whole-of-site investigations and modelling that will enable a more comprehensive, whole-of-site environmental impact assessment. This assessment will be required for ERA to demonstrate their ability to achieve the Environmental Requirements.

The proposed conditions also stipulate that ERA provide additional information on the controls used to manage key risks associated with the long-term storage of tailings in Pit 1, as well as a contingency plan detailing mitigation measures for future implementation, if required.

Please contact Keith Tayler in the first instance on 08 8920 1101 should you wish to discuss further.

Yours sincerely

Matthew Whitfort
A/g Supervising Scientist

Attachment
A: Environmental Assessment: Ranger Pit 1 Final Tailings Deposition Level to +7 mRL

Recommended Approval Conditions

Based on the best available information and modelling the Supervising Scientist supports the approval of a final tailings level of +7 mRL in Pit 1 of the Ranger uranium mine, subject to the following conditions:

1. **Bulk backfill.** Prior to the commencement of any further Pit 1 backfill works ERA must provide a detailed Pit 1 backfill plan for the approval of the Director with the advice of the Supervising Scientist. The plan must demonstrate how the work will reconcile assumptions made in the tailings consolidation model and should include a detailed method and schedule for fill placement, and a comprehensive monitoring program for tailings consolidation, including settlement surveys and water balance measurements.
2. **Landform design.** Prior to commencing the placement of the final six million tons of backfill in Pit 1 ERA must have obtained approval for the final landform design from the Director with the advice of the Supervising Scientist. The design must specifically address issues including plant available water, the potential for plant root interactions with tailings and the formation of gullies over the top of tailings.
3. Within eight weeks of the release of this report ERA should propose a schedule for completion of each of the following for the approval of the Director with the advice of the Supervising Scientist:
    a. **Risk assessment.** A revised environmental risk assessment that clearly indicates how each risk was identified, how each risk scenario was evaluated, and how the risk ratings and related management classes were assigned. The assessment must clearly describe each of the existing and proposed controls, including demonstrating how effectiveness and manageability of each control was ranked.
    b. **Geochemistry.** A reactive-transport model for calcium in groundwater and further characterisation of source terms in and around Pit 1, including saturated waste rock, pit tailings flux and groundwater surrounding Pit 1.
    c. **Tailings consolidation.** A plan that outlines an approach to ongoing verification of the tailings consolidation model, which should enable refinement of the pit tailings flux source term for contaminant transport modelling as well as an ongoing understanding of how the groundwater system will respond throughout the bulk backfill process. The plan must include a detailed evaluation of model uncertainty, a monitoring program for settlement plates in Pit 1 and a monitoring program that enables better understanding of the Pit 1 water balance (including measurement of the quantity and conductivity of decant water removed from the pit).
    d. **Groundwater modelling.** Additional groundwater modelling to better estimate the timing and magnitude of contaminant delivery to Corridor Creek throughout the seasonal stream-flow cycle and to better understand the initial period of groundwater stabilisation. Groundwater modelling must be conducted in consideration of groundwater/surface water interactions to allow integration with surface water modelling. Further investigation should be carried out on specific hydrogeological zones that represent potential pathways (e.g. the 'MBL zone' and the Lower Mine Sequence carbonate zone between Pit 1 and Pit 3).
    e. **Surface water modelling.** Additional surface water modelling for the Ranger site and surrounds, including the Corridor and Magela Creek systems, to estimate post-closure surface water flows and associated concentrations of contaminants in surface waters at a resolution suitable for aquatic toxicity assessment. Surface

water modelling must be conducted in consideration of groundwater/surface water interactions to allow integration with groundwater modelling.

f. **Groundwater monitoring.** A groundwater monitoring program appropriate for further refinement of the Ranger hydrogeological conceptualisation, ongoing model validation and early detection of seepage from Pit 1. The program must include a schedule for the routine measurement of groundwater levels, quality and gradients at key locations along with trigger values that can be used to identify seepage from the pit and provide the basis on which to consider implementing contingency measures. Where these locations differ to those in the current Pit 1 monitoring program, as approved in 2005, justification must be provided.

g. **Contingency planning**. A contingency plan that explicitly details all controls that are currently in place to reduce environmental risk, and any planned contingency measures that can be implemented to mitigate impacts in the event that monitoring detects concentrations of contaminants in groundwater that are in excess of those predicted or are likely to be of environmental significance.

Appendix 2

Supervising Scientist Branch review of Pit 1 Notification: final in-pit tailings level

Australian Government

Department of the Environment and Energy

Supervising Scientist

SSB Document Review Comments Form

Application / Proposal Title:	Pit 1 Notification – Final in-pit tailings level (Notification of Pit 1 Final Tailings Level to +7mRL) and appendices dated 16 March 2016
Comments Provided:	15 November 2016

Section Reference	Comment
General	As a general comment to the Pit 1 Notification relating to the modelling (Section 5), primarily for groundwater (Appendix D) but also consolidation (Appendix C), key supporting evidence and information was missing from the main text within the Notification in order to justify conclusions. Frequently the reader was required to search for supporting statements held within the appendices or more often than not required the reader to consult references linked to the appendices such as ATC Williams 2012 (consolidation analysis) and INTERA 2014a (Pit 3 closure modelling). Even then statements weren't explicit in terms of providing supporting information in the context of the Notification. Furthermore information in support of the numerical groundwater model was provided in the recently received (August 2016) INTERA 2016 (Ranger conceptual model) report.
General	Groundwater modelling does not explicitly consider fracture flow. This has implications for the solute transport modelling. One implication is that the effective porosity in fracture flow systems can be substantially lower than bulk porosity. Work by Turner et al. (2014: pp376–77) shows this to be the case on the Ranger site in the vicinity of Pit 1. The effect of this would be to reduce the travel times; it would be unlikely to affect the predicted annual flux of contaminants. Given the year in which the peak flux of contaminants occurs is immaterial (so long as it is within 10,000 years), the choice of porosity values is not important to the applicability of the model. The numerical model has only been calibrated based on groundwater heads from 2005–06 (INTERA 2014a). While a longer calibration period would give greater confidence in the results of the modelling, it is recognised that there are limitations with the available data, though it is noted there is other data that could have been used. For this reason, as noted below (comments on Appendix A) in reference to monitoring, groundwater monitoring in the lead-up to

Section Reference	Comment
	decommissioning should be undertaken with a view to validating and hence reducing uncertainty in the models. Model calibration to a longer and/or wider dataset would likely result in refinements to hydraulic parameters. This would be expected to result in more accurate predictions of the timing of peak solute flux to Corridor Creek. However, given the way that the model has been constructed, it would be unlikely to increase the magnitude of the peak contaminant flux.
3.2	It would be useful to be more explicit regarding how average tailings levels are derived i.e. states "at the end of deposition (i.e. 2008), the average tailings level was less than +12 mRL". Fig. 1 missing location of decant towers/structures. For Figs. 1a, 2, 3, 4 it would be useful to show any engineering works i.e. the seepage limiting barrier (SLB). It is understood that the "consolidation model predicted that the average final tailings level in Pit 1 would be +7 mRL..." it would be useful to be more explicit as to when (i.e. year) this will occur and under what conditions.
4.1	There is discussion of "tailings placed above 0 mRL may allow contaminated seepage to egress via shallow aquifers along the south eastern zone of the pit wall...solutes would then enter Magela Creek at concentrations potentially in excess of the receiving water criteria". While the SLB was installed to mitigate this issue (if tailings are placed above 0 mRL), the SLB has been breached and longevity of any engineering structures over 10,000 years is questionable. There is reference (i.e. no documented detail provided in the Notification) to risk assessments that have been conducted in the likely hood of no SLB, however it is still unclear (due to the lack of detail) why there is no longer a concern of tailings being placed above 0 mRL. MBL aquifer has been introduced as a key hydrogeological feature that could influence groundwater movement however there is no clarity around what the MBL aquifer actually is (i.e. is it a zone?).
4.2.2.3	Aside from one line identifying Class III as high risk, there does not appear to be a concise description or explanation of the significance of risk rankings classified as I – III, or how they were derived or identified.
4.2.2.4.2	Derived dilution factor (for Corridor Creek) is based on ratio of average predicted seepage rate from Pit 1 to base flow in Corridor Creek. The actual receiving stream concentration may be underestimated, especially towards the end of the wet season, if the egress of solutes lags the recessional fall in stream flow. Flow duration character of Corridor Creek would be useful to evaluate the dilution flow requirements.
4.2.2.4.3	Reference to the horizontal and vertical spatial resolution of the DEM representing the landforms is missing; the resolution of the model is key to this discussion. The DEM representing the landform surface has a horizontal resolution

Section Reference	Comment
	of 10 m (note vertical resolution could be >10 m). Consequently, care should be taken not to interpret model predictions as absolute depths but rather an indication. Risk assessments on differences between a predicted final tailings level and a predicted erosion depth on a relatively coarse elevation from the landform model may result in an inaccurate risk assessment.
4.2.2.4.4	The thickness of the waste rock cover (i.e. >20 m) is likely to be sufficient to ensure tree roots do not penetrate into the tailings. However, the reference to research (i.e. Hutley et al. 2000) showing that tree roots are mainly found within the top 1 m of soil could be misinterpreted, given that tree roots in tropical savannas can penetrate to much greater depths (e.g. 12 – 15 m).
5	Current groundwater modelling shows impacts to Corridor Creek are unlikely, but further refinement of the modelling is required. SSB accepts that the information provided is sufficient to show that impacts off the Ranger Project Area (“surrounding environment”) as a result of contaminants arising from the Pit 1 tailings are unlikely.
5.1.1	Fig. 3.24 presents the predicted annual Mg loading to Corridor Creek from Pit 1 from sources such as tailings, waste rock and the pit tailings flux (PTF) at a predicted 95% removal case however a more conservative approach is to consider PTF at the 90% removal case represented in Table 6 and Appendix D 3.23. The Mg loading to Corridor Creek continues to increase up to the end of the model run time of 10,000 years. It appears that the loading to Corridor Creek may increase above 2.29 tonnes per annum beyond the 10,000 year model run time. If the hydraulic parameters of the model do not adequately represent the groundwater flow or solute reaction conditions of the site, a greater annual flux of tailings-derived contaminants may reach Corridor Creek within 10,000 years. Thus, the model may under-predict the peak load and timing for the tailings Mg source to be expressed at Corridor Creek.
5.1.1	The major sensitivity for solute egress from Pit 1 over the 1st 50 years will be the amount of PTF that is initially extracted as the tailings consolidates over the first 6 years, including the time required for placement of backfill. Extracting the PTF as it is produced will be the key to ensuring that downstream environmental impact is minimised. It is inferred by ERA in its Notification for Pit 1 closure (ERA 2016) that 99% of the PTF will be removed. This reviewer disagrees with this proposition. In the absence of guidance to the contrary it has been assumed for this review that 90% removal is more realistic (expressed by OWS above). The combined effects through time of Pits 1 and 3 need to be considered. Simple addition of the predicted Mg loads from each pit through time provides a reasonable first pass basis for doing this. Running a combined pits model would probably not provide much more insight. However, in this context it appears that the pre-existing (impacted) solute loads

Section Reference	Comment
	in groundwater in the areas between the domains defined by the pit footprints may not have been taken into account by the model. There will also be a substantial amount of waste rock remaining on the surface after the pits are backfilled. The contribution of this solute source to annual loads of Mg leaving the site may not have been adequately addressed by the model, and could be significant. The magnitude of the PTF-derived source in Pit 1 may have been significantly underestimated by virtue of a higher transient elevation of the PTF occurring in waste rock, compared with the model assumption that the final elevation corresponding to a given % removal is the starting point for the model. This is an issue since the PTF-wetted material will retain a significant proportion of the PTF solute load, despite subsequent drain down to the target removal level.
5.1.1	Figure 8 shows a time series of the predicted mass of Mg released from the waste rock and also the tailings sources that appears to be reasonable except for the substantial decrease in Mg load from the waste rock source immediately after 270 years. This sudden change is not explained (simplistic statements to the effect that the peak occurs at year 270 do not form an explanation, although detailed explanations may be made in other reports not sighted).
5.1.3	The Mg ratio approach to estimating concentrations (and loadings) of COPC discharged from the site through time is appropriate, assuming conservative behaviour for them. However, the predictions may not necessarily be valid given the likely underestimation of some of the contributing source terms.
6.1	From a modelling perspective, it should also be noted that only limited rainfall scenarios were incorporated into model simulations to date. Similarly the simulations did not attempt to model the effect of armouring the surface. As above when quoting model predictions, it is also important to recognise that the DEM representing the landform surface has a horizontal resolution of 10 m (vertical resolution could be >10 m). This has implications in terms of accurately predicting erosion depth and distance/depth between gullies and buried tailings.
6.1.1	To be specific, the Supervising Scientist provided surfaces which had been modelled for a simulated period of 10,000 years. The source landform on which the simulations were based were supplied by ERA. The statement that “the risk of exposure of tailings at final consolidated level over a 10,000 year period is considered very low” assumes that the predicted erosion depths are absolute. Note the earlier comment that due to the resolution of the DEM, predicted erosion depths should only be considered as an indicator of potential erosion – further erosion may occur, and the separation between buried tailings and exposure may potentially be less, which may not mean a very low risk.

Section Reference	Comment
	Some concern about where the gullies have been shown to develop in Fig. 13. Potentially these gullies are located where the cover over Pit 1 is the thinnest as shown in Fig. 14.
7.1, 7.2 & 7.3	No temporal aspect is included with the largely qualitative assessment of potential radiation exposure pathways. The assessment of radon decay product and external gamma pathways in particular seem to relate to the initial conditions of the as-built landform. There is no consideration of potential increases in radon exhalation from tailings in areas of gully formation over the 10,000 year period. Section 6.1.1 of the report indicates that gullies may come to within 5 vertical m of the top of the tailings within 10,000 years, which means an increase in radon exhalation in those areas. The radiological significance of such temporal changes should be discussed. No radiological characterisation of the tailings (other than gamma dose rates) is provided in the report. What are the activity concentrations of uranium series radionuclides (particularly radium-226) in the tailings? What are the typical radon exhalation fluxes from the uncovered tailings? This would help with the interpretation of some of the information in Section 7. For example, it would enable determination of the actual flux of tailings-related radon out of the surface cap, rather than just knowing the percentage reduction. The report only considers the potential radiation impacts from the tailings material alone. It does not consider the radiation impacts from the 1's and 2's grade material that will cap the tailings. Radiation impacts from the capping material are likely to be much larger than those from the tailings.
9.2	SLB mentioned in text however the location is missing from Fig. 19, only bores MB-L and R1C3-1 (and proposed new bores) are shown. Pit 1 numerical groundwater model validation should be a key objective of the groundwater monitoring program (as discussed below for Appendix A). It would be useful to know where the bores used in model calibration are or were and what aquifer they monitored. Only 5 bores are proposed for groundwater monitoring which is very limited (Table 11). While final depths of new bores may change, the bore design suggests long screens which implies the bore may potentially screen multiple aquifers. It would be useful to have "aquifer monitored" as a field in Table 11. It would be useful to monitor the "shallow weathered rock", the "deep weathered bedrock", the MBL zone (multiple bores), the "undifferentiated bedrock" and set up bore transects not only parallel to Corridor Creek but perpendicular (between the pit and the creek).

Section Reference	Comment
Appendix A	It is recommended that a groundwater monitoring plan be developed with the explicit aim of reducing uncertainty in the numerical groundwater model. The plan documented here outlines surface water monitoring and groundwater monitoring in the vicinity of Pit 1. However, there is no discussion of how the monitoring will improve understanding of the hydrogeological system or allow validation (or recalibration) of the numerical model. Improving confidence in numerical modelling (through validation and/or addition to the calibration dataset) should be a key aim of a monitoring program. To improve modelling confidence, the monitoring plan will need to include, as a minimum, monitoring of groundwater levels, quality and gradients.
Appendix B 4.3	States "waste rock used to cover the geotextile must be limited to 0.5 m maximum particle size" and that "it will be necessary to remove rocks larger than 0.5 m particle size at the waste rock dump". No information on how this will be conducted; presumably the rock will have to be screened to remove those larger than 0.5 m.
Appendix A 4.4.2 & 5.3	It is not clear whether statements of expressed pore water percentages are based on assumptions (or perhaps are rules of thumb derived from interpretations of model results), or are actually results from the consolidation model. For example, Section 5.3 states that about 60% of the expressed pore water reports as upwards flow (and thus would be decanted, in which case, one would expect to see volume measurements documented), while Section 4.4.2 states that "40-45%" reports as downwards flow (and thus is lost to groundwater, which cannot be measured directly, and thus it remains a fundamental uncertainty).
Appendix D TOC	Page numbers are missing for figures.
Appendix D Exec summary	States "PTF source only persists for several decades". Should be more specific than "several". States "in the context of environmental modelling under uncertainty, a conservative approach is one that intentionally increases the likelihood that impacts will occur when selecting from ranges of uncertain model inputs" however a general comment to Appendix D and Pit 1 modelling is whether a conservative approach has consistently been applied. See comments below related to sections of Appendix D.
Appendix D 2.1	Although calcium (Ca) is not a COPC, it should be included in the suite of solutes modelled due to its strong ameliorative effect on magnesium (Mg) toxicity, i.e. Mg:Ca ratio is important for determining toxicity and guideline values (GVs). However, the conservative approach for solute transport modelling Ca will need to be considered given its "protective" function.
Appendix D 2.2	"Source concentrations for Mg, U, Mn, and Ra-226 in waste rock backfill were estimated using the arithmetic mean to

Section Reference	Comment
	represent the relatively larger data set for saturated waste rock." No statistics reported, i.e. sample numbers, max, mins etc.
Appendix D 2.2.1	"A combination of predominantly 1s and some 2s waste rock will be used to create the saturated waste rock above the tailings". No specific proportions stated. "Geochemical analyses of samples from bores that represent undisturbed groundwaters in the Ranger area were used as the basis for determining source concentrations for the saturated waste rock backfill in Pit 1". Use of the term "undisturbed groundwaters" is misleading. Undisturbed suggests that these groundwaters are background however the passage suggests groundwaters are contaminated by stockpiles.
Appendix D 2.2.1	The Mg source concentration assigned by INTERA for the vadose zone waste rock backfill is consistent with the existing empirical data set for Type 1 waters (the most relevant). In contrast, the source strength for this zone may have been substantially underestimated for U. The source terms for laterally inflowing groundwater have been underestimated, especially for the shorter term, given the likely presence of waste rock and tailings dam leachates in the up-gradient groundwater flow field. INTERA has assigned country rock (background) COPC values to this source in perpetuity. The initial COPC source strength of the saturated zone of waste rock has likely been under-estimated (substantially so for U) as it has been assigned "background" source strength in perpetuity. In practice this rock will contain a pre-existing elevated leachable load that will be eluted through time. This issue is likely to be of most import for Pit 3 given the greater thickness of this layer than for Pit 1. The use of a geochemical model coupling pyrite oxidation with dissolution of Mg (from chlorite) to predict the length of the time window for elution of above background concentrations of Mg from the waste rock vadose zone should be regarded as indicative only, given the numbers of assumptions that had to be made about initial pyrite content and oxygen concentrations in the backfill.
Appendix D 2.2.2	States "0.874 quantile (87.4 percentile)". No justification for using this percentile. However the use of the 87.4 quantile (i.e. percentile) of the data set is appropriate to define the composition of the tailings pore water and PTF source terms. This is because the 87.4 quantile is even higher than the 80th percentile that is usually used as the basis for delimiting water quality data for environmental assessments (ANZECC and ARMCANZ 2000).

Section Reference	Comment
Appendix D 3.1	Using removal of 90% of the PTF volume is a more conservative approach than using 95% (as expressed previously).
Appendix D 3.4.2	As above confusion over what is meant by groundwater "background concentrations". 60 mg/L should not be considered as "background".
Appendix D 3.3.4	Important in the behaviour of the modelled system is the hydraulic conductivity of the tailings, which is low compared to neighbouring hydrolithologic units. The tailings have been assigned a hydraulic conductivity value of 1.0 x 10^{-3} m/d, compared to 4.8 x 10^{-2} m/d for shallow weathered rock and 8.5 x 10^{-3} m/d for deep weathered rock. The low tailings hydraulic conductivity limits the rate at which tailings pore water is able to flow towards Corridor Creek. Limited information is available although it is noted that key information sources are ATC Williams 2013 (e-mail as per INTERA 2014a) and Williams et al. (2007).

Appendix 3

Office of Water Science Branch review of Pit 1 Notification: final in-pit tailings level

PIT 1 FINAL TAILINGS LEVEL ADVICE

Recommendations:

1. That the application to have an average final tailings level of +7 mAHD be approved.
    a. This recommendation is based on the potentially greater risk to the surrounding environment from the resultant higher tailings level in Pit 3 and its proximity to Magela Creek.
2. That the Department undertakes further work to identify key knowledge gaps particularly in regards to the MBL zone[1] and potential, seasonal, impacts on Corridor Creek and Georgetown Billabong.

Issue

1. ERA received approval in 1995 for deposition of tailings in Pit 1 to RL0 m and commenced deposition in August 1996 (NT Government 2005; ERA 2005: p4). Approval for deposition to proceed to an interim level of RL12m was provided in 2005 and deposition ceased at this level in Nov–Dec 2008 (ERA 2016 Appendix D: p4).
2. ERA is seeking approval of a final consolidated tailings level of approximately 7 mRL. The level of 7 mRL is the estimated average level that these tailings will consolidate to but reflects a range from up to 15 mRL at the edge of the pit (though 12 mRL around most of the pit's circumference) to less than 1 mRL near the middle of the pit (Appendix D: Figure 3.1). The crest of the pit is approximately 19 mRL at its lowest point (Energy Resources Australia 2016: p8).
3. A number of documents have been provided as evidence that the final tailings level will meet the requirements of Ranger Authorisation 0108-17 granted under the Northern Territory *Mining Management Act 2013*. Schedule 5.8 of the Ranger Authorisation states:

    Final disposal of tailings shall be undertaken to the satisfaction of the Minister on the basis of best available modelling, in such a way to ensure that:

    5.8.1 the tailings are physically isolated from the environment for at least 10,000 years;

    5.8.2 any contaminants arising from the tailings will not result in any detrimental environmental impact for at least 10,000 years;

    5.8.3 radiation doses to members of the public will comply with relevant Australian law and be less than limits recommended by the most recently published and relevant Australian standards, codes of practice and guidelines effective at the time of the final disposal; and

    5.8.4 by the end of operations all tailings must be placed in the mined out pits

Issues in regards to tailings deposition

Given legislative requirements[2], the only alternative to approval of the currently proposed final tailings level for Pit 1 is to remove tailings from Pit 1 and place them in Pit 3.

[1] MBL zone (literally "mine bore L zone") refers to a high hydraulic conductivity zone between Pit 1 and Corridor Creek.

4. Below the zone of weathering, the Ranger Mine Lease area occurs within an area dominated by igneous or recrystallised metamorphic rocks. This type of geology is composed of a crystalline matrix where groundwater flow is largely through fracture networks and bulk permeability is low. Fractures in crystalline rocks are likely to increase in connectivity, length and aperture in proximity to the surface or structural features. While the shallow alluvial and weathered rock zones contain bulk flow groundwater systems, the Office of Water Science considers that the deeper hydrogeology at Ranger is likely to be dominated by a range of structural features and fracture networks of varying scale. The groundwater flow system is complex, and is likely controlled by a mix of primary and secondary porosity features that vary across the site (see Appendix 3 for examples of Pit 1 inflows through a fracture network).

5. The MBL zone is of particular importance for solute transport from Pit 1 to Corridor Creek. This zone is described by Anderson et al. (2009) as occurring adjacent to pegmatites, presumably the alteration zone affected by the pegmatite intrusions. Anderson et al. (2009: p10) describe it as being "up to 350 m wide along a major fault zone generally aligned with Corridor Creek." It is not considered to actually intersect Pit 1, as if it did, substantially greater pit inflows would have resulted from the high hydraulic conductivity (Anderson et al. 2009: p10). Further details regarding the representation of the MBL zone within the solute transport model are in Appendix 1.

6. Modelling has also been undertaken for simulation of solute transport from Pit 3: the same base model as used for Pit 1. Pit 3 is located substantially closer to Magela Creek than is Pit 1, making isolation of contaminants in the pit from Magela Creek potentially more challenging. The edge of Pit 3 is located around 100 m from Magela Creek, whereas Pit 1 is located around 150 m from Corridor Creek, a tributary of Magela Creek. Concerns about the modelling in regards to Pit 1 are presented in Appendix 1.

7. The presence and location of the Djalkmara Sands on the north-eastern side of Pit 3 provides a high conductive zone that could provide a conduit for COPCs to enter Magela Creek. Removal of some of the tailings from Pit 1 into Pit 3 may result in tailings directly 'resting' against these sands, which is a situation that should be avoided. Further the Office of Water Science has ongoing concerns in regards to the fault 'zone' in the northern side of Pit 3, and possibly the carbonate unit, as potential pathways for COPCs into Magela Creek.

8. Removal of tailings from Pit 1 into Pit 3 may require changes in the final landform, which has already been planned and is subject to a separate approval process.

9. Deposition of additional tailings in Pit 3 may also increase the erosion risks. The Office of Water Science is also concerned about the erosion risks potentially associated with the backfilled Pit 3. Djalkmara Billabong was removed when Pit 3 was mined. It is understood that the final landform will be designed to have a new watercourse (i.e. upstream segment of the old Djalkmara Creek) form to the east of Pit 3. However, if the watercourse were to reform near its original location, erosion could potentially expose tailings deposited in Pit 3. Having the tailings at a higher elevation than currently planned would result in a thinner layer of waste rock 'protecting' the tailings from direct erosion. A higher elevation of tailings in Pit 3 is the inevitable consequence of a lower final tailings elevation in Pit 1, since

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[2] Ranger Authorisation 0108-17, schedule 5: 5.8.4 and *Atomic Energy Act 1953* Section 41 Authority, Appendix A, section 11 paragraph 11.2

tailings are legislatively required to be deposited in the pits (Ranger Authorisation 0108-17, schedule 5.8.4).

Monitoring

10. The Office of Water Science recommends that a groundwater monitoring plan be developed with the explicit aim of reducing uncertainty in the numerical groundwater model. A monitoring plan was submitted as Appendix A to the Notification (ERA 2016). It outlines surface water monitoring and groundwater monitoring in the vicinity of Pit 1. However, there is no discussion of how the monitoring will improve understanding of the hydrogeological system or allow validation (or recalibration) of the numerical model. The Office of Water Science considers that improving confidence in numerical modelling (through validation and/or addition to the calibration dataset) should be a key aim of a monitoring program. To improve modelling confidence, the monitoring plan will need to include, as a minimum, monitoring of groundwater levels, quality and gradients.

11. As stated above, the Office of Water Science considers that the model is fit for the immediate purpose of making a decision on the final tailings level in Pit 1; nevertheless, it considers that a revised monitoring plan with this aim should be prepared.

Further work

12. The Department will undertake further work to identify key information gaps that need to be addressed by the proponent to inform ongoing management and closure of the site. This work would include, but not be limited to:

    a. Finer-scale understanding of the MBL zone, including preferential pathways; surface water-groundwater interactions; and the implications for seasonal and local-scale surface water solute concentrations to impact on Corridor Creek and Georgetown Billabong.

    b. Targeted groundwater monitoring for the purpose of validation to reduce uncertainty associated with the numerical groundwater model.

    c. Investigation of erosional risks associated with the final landform including break-of-slope erosion.

    d. Confirmation of solute source terms, particularly for the waste rock and confirmation of the consolidation characteristics of Pit 1.

13. If this further work were to identify significant environmental issues, given the closure constraints, geotechnical solutions would need to be looked to. Remediation options could include measures such as interception trenches, grout curtains and partial extraction of tailings from the pit edge.

Appendix 1 - Modelling Assumptions and Concerns

14. ERA commissioned a solute transport model to conservatively evaluate annual peak load to Corridor Creek each year for a 10 000-year simulation period. While the model has a number of limitations – some of them substantial – the Office of Water Science considers it sufficient for this purpose. Issues and concerns with the assumptions used and the modelling process are outlined briefly below.

Non-reactive transport

15. The modelling assumes that all contaminants of potential concern (COPCs) are non-reactive. Thus, their relative concentrations at the point of discharge into the surface water system are the same as the initial concentrations. Magnesium is considered to be a contaminant of potential concern (Intera 2016 Appendix D: p 8). Mg is considered a non-reactive or *conservative* solute, that is, its concentration will not be reduced by geochemical reactions along its flowpath (Intera 2014 App D: pp8, 11–12). The other COPCs – namely, U, Mn, ^{226}Ra, available nitrogen (reported as total available nitrogen, TAN), nitrate (reported as nitrogen, NO_3-N), total-P and ^{210}Po – are thought to be reactive that is, reduce in concentration through geochemical reactions. They have, however, been modelled as being conservative (Intera 2014 App D: p8). The predicted concentrations and fluxes for reactive COPCs would therefore over-estimate actual values, presuming other assumptions to be accurate.

16. This modelling indicates that annual flux of magnesium from Pit 1 tailings will peak at 2.29 tonnes per year[3] (ERA 2016 Appendix D: p25) which is within the 10 000 year statutory timeframe. This compares to a total estimated 178 tonnes per annum average for the whole Ranger Uranium Mine site during operation (Intera 2016: p251). In the context of post-closure impacts, by far the largest predicted impact is from the waste rock (pit waste rock and landform waste rock), from which a peak of 138[4] tonnes per annum of magnesium are expected to migrate to Magela Creek (Intera 206: p253). In this context, the environmental impact indicated by the modelling from tailings in Pit 1 is negligible.

17. However this is based on the modelled result of the tailings pore water not entering, in any substantive way, Corridor Creek until 10 000 years post closure. The magnesium loading to Corridor Creek continues to increase up to the end of the model run time of 10 000 years. It appears that the tailings source loading to Corridor Creek may increase above 2.29 tonnes per year beyond the 10 000 year model run time. If the hydraulic parameters of the model do not adequately represent the groundwater flow or solute reaction conditions of the site, a greater annual flux of tailings-derived contaminants may reach Corridor Creek within 10 000 years. Thus, the model may under-predict the peak load and timing for the tailings magnesium source to be expressed at Corridor Creek.

18. Because of both the attenuation expected for COPCs other than Mg and the surface water limit values for COPCs compared with the initial concentrations (see ERA 2014: p55 and ERA 2016 Appendix A: p2), in the event of water quality criteria being exceeded, it is likely that Mg would be the first COPC to exceed limits. Both for this reason and because all

[3] Note that this figure is calculated assuming 90% of tailings flux removal prior to closure. Predictions were also provided for 99% tailings flux removal, but that estimate is less conservative and so is not quoted in this document.
[4] Comprising 137 tonnes via groundwater and <0.8 tonnes through direct runoff.

contaminants are modelled as being in constant proportion to one another, discussion of modelling results can appropriately only (explicitly) consider Mg concentration.

19. The Office of Water Science contracted Dr David Jones to provide advice on geochemical aspects of the Pit 1 and Pit 3 modelling. In his advice, Jones (2016) raised concerns regarding the initial concentrations used for a number of COPCs. Further investigation of this issue may alter somewhat the relative concentrations of different COPCs. Nevertheless, given the extremely low predicted flux of COPCs from Pit 1 to the surface water system, the Office of Water Science does not consider this a major issue regarding making a decision on the final tailings level in Pit 1. It will be a focus for further work by the Department to inform other closure considerations. Jones (2016) also raised concerns about the way that calcium had been modelled, given its ameliorative role in magnesium toxicity. This will also be a focus for further work by the Department.

Time period

20. It is assumed in the modelling that Pit 1 is fully resaturated at the start of the simulation period. ERA suggest (2016 App D: p20) that this is likely to have the effect of shortening the transport time and is therefore a conservative assumption. As the peak contaminant flux from the pit to the surface water system occurs within a few centuries – well within the 10 000-year period under consideration – the Office of Water Science considers that, this and other assumptions that affect the timing of the estimated peak in contaminant flux are unlikely to affect the conclusions drawn from modelling.

21. Whether all the predicted pore tailings flux is removed remains questionable. To date no measurements of expressed water from the tailings has been provided as noted in Middlemis (2016). It is also based on an assumed (modelled) porosity for the tailings. Further the consolidation modelling assumes that between 35–40% of the tailings pore fluid will be lost through the bottom of the pit. Given the likely hydraulic conductivities at this depth this is deemed unlikely in the timeframe of the modelled consolidation. Consequently this requires further investigation.

Boundaries

22. Features interpreted as groundwater divides were incorporated into Intera's model as no-flow boundaries (Intera 2016 App D: p16). The northern boundary follows the north bank of Magela Creek. The eastern boundary is the ridge near to Corridor Creek. Intera argue that making the Magela Creek boundary a no-flow boundary is conservative, as it forces all groundwater flowing north in the direction of Magela Creek to enter the creek.

23. The southern boundary – also a no-flow boundary – is aligned with the Ranger fault. The interpretation of this fault area as a groundwater barrier is consistent with its treatment by other authors. For example, Anderson et al. (2009: p18) also consider the Ranger Fault to be a low permeability zone. The Office of Water Science considers that the representation of the southern boundary is also appropriate based on the available evidence but notes that it is rare for a fault of this size to be a hydraulic barrier along its entire length.

Hydraulic parameters

24. Intera's model uses 30 layers to represent the hydrogeology, with model cells measuring 25 x 25 m (ERA 2014: p63). The model contains approximately half a million cells.

25. Hydraulic conductivity values used in the model have been determined partly through model calibration and partly based on field testing. It is stated that hydraulic conductivity values, along with other parameters, were based on the results of modelling for Pit 3 for the uppermost 12 layers. The validity of this assumption needs to be further explored. Values for the Hanging Wall Sequence, Upper Mine Sequence, Lower Mine Sequence, Deeps water-producing zone and the Nanambu Complex "were assigned based on the results from the straddle-packer testing and flow measurements in exploration bores" (ERA 2016 App D: p19). Given the construction of the model, with model boundaries that force contaminant flux into Corridor Creek, changes in hydraulic conductivity values would be unlikely to alter the magnitude of the peak contaminant flux, although they could alter its timing.

26. The MBL aquifer is represented in the model as a higher hydraulic conductivity zone: $K_h = 2.54 \times 10^{-1}$ m/d (Intera 2016 Appendix D: p18). As previously noted, this is considered an important zone for transport of COPCs from Pit 1 to Corridor Creek. Consistent with this, the model shows groundwater flow "east across Pit 1 into the MBL zone and along the Corridor Creek drainage" (ERA 2016 Appendix D: p22). Whilst in a gross sense this is appropriate, the potential for preferential pathways in the MBL aquifer has not been considered.

27. Further, analysis of drilling data by the Office of Water Science indicates that the MBL zone may be deeper than that represented in the model.

28. Important in the behaviour of the modelled system is the hydraulic conductivity of the tailings, which is low compared to neighbouring hydrolithologic units. The tailings have been assigned a hydraulic conductivity value of 1.0×10^{-3} m/d, compared to 4.8×10^{-2} m/d for shallow weathered rock and 8.5×10^{-3} m/d for deep weathered rock. The low tailings hydraulic conductivity limits the rate at which tailings pore water is able to flow towards Magela Creek. The hydraulic conductivity value for the tailings was based on analysis undertaken by ATC Williams in 2013 (ERA 2014: pp22–23). The Office of Water Science has not been able to review this document. However the value appears reasonable based on the (somewhat limited) information provided in Williams et al. (2007).

29. The seepage barrier is represented in the model. Groundwater flow, as commented on by the independent reviewer (ERA 2016: Appendix E) flows around the barrier as modelled, including through exfiltrating. The barrier is therefore ineffective in retarding (and certainly in preventing) flow of COPCs from Pit 1 to Corridor Creek post closure: which is not surprising, as this was not its design purpose. The Office of Water Science considers that the barrier is likely to be a less effective barrier than modelled, particularly over the 10 000-year simulation period; however, this is not likely to significantly affect the conclusions from the model, given that groundwater flow in the model readily flows around the barrier. The barrier as modelled would (compared to no barrier) increase the transport time for solute getting to Corridor Creek through direct groundwater discharge. Conversely, groundwater that is forced to the surface by the barrier (as modelled) would travel to Corridor Creek more slowly without the barrier.

30. The proponent's modelling does not explicitly consider fracture flow. This has implications for the solute transport modelling. One implication is that the *effective* porosity in fracture flow systems can be substantially lower than bulk porosity. Work by Turner et al. (2014: pp376–77) shows this to be the case on the Ranger site in the vicinity of Pit 1. The effect of this would be to reduce the travel times; it would be unlikely to affect the predicted annual flux of contaminants. Given the year in which the peak flux of contaminants occurs

is immaterial (so long as it is within 10 000 years), the choice of porosity values is not important to the applicability of the model.

31. Another potential implication of fracture flow is that there is the potential for preferential flow pathways. This could result in localised high concentrations of contaminants. The implications of this for the Ranger site should be further explored.

Model calibration

32. The numerical model has only been calibrated based on groundwater heads from 2005–06 (ERA 2006: p23). While a longer calibration period would give greater confidence in the results of modelling, the Office of Water Science recognises that there are limitations with the available data, though notes there is other data that could have been used. For this reason, as noted in the *monitoring* section of this report, monitoring in the lead-up to decommissioning should be undertaken with a view to validating and hence reducing uncertainty in the modelling.

33. Despite limitations of the calibration, the Office of Water Science considers that the existing modelling is sufficient for making a decision on the final Pit 1 tailings level. Model calibration to a longer and/or wider dataset would likely result in refinements to hydraulic parameters. This would be expected to result in more accurate predictions of the timing of peak solute flux to Corridor Creek. However, given the way that the model has been constructed, it would be unlikely to increase the magnitude of the peak contaminant flux.

Exfiltration

34. Numerical groundwater modelling also indicates that some groundwater will discharge to the surface, i.e. *exfiltrate* (Intera 2016 Appendix D: p7). These are the two paths by which COPCs arising from Pit 1 can reach the surface water system: groundwater discharge into Corridor Creek and groundwater exfiltration, with subsequent surface flow, following the topography, to Corridor Creek. It is therefore accounted for within the modelling. Any environmental impacts from this groundwater exfiltration would be highly localised, given the small solute flux involved.

Appendix 2 – Geology

35. A number of structural features have been mapped and intersected by the excavation of Pit 1. Faults and shear structures are predominately reverse, indicating they formed during a compressional regime (Hein 2002). These include a major shear zone at the contact between the Nanambu and Cahill Formations, a shear zone within the lower mine sequence (also known as the lenticular schist) and an "upper thrust" fault within the upper and lower mine sequences (Savory 1994; Hein 2002). The upper thrust fault is a significant structure which resulted in up to 200 m of displacement in the vicinity of Pit 1. Water seepages into the pit occurred where the upper thrust fault structure intersected the wall of Pit 1 (Savory 1994).

36. Many other small scale shears and faults have also been mapped or intersected by the excavation of the pit. These features typically occur at the contacts between different rock types, close to the weathered zone or associated with the contacts with pegmatite intrusions (Hein 2002). For example, shears located along the contact between a pegmatite vein and weathered rock were encountered during construction of the seepage limiting barrier at approximately 1 and 3 mAHD (URS 2006: p3-8). These features allowed sufficient flows of water to hinder construction of the barrier.

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Appendix 4

Hydrogeologic Pty Ltd – Pit 1 consolidation model review: *Ranger Pit 1 Consolidation Modelling Independent Review*

RANGER PIT 1 CONSOLIDATION MODELLING INDEPENDENT REVIEW

Prepared for:	Supervising Scientist Branch (Department of Environment)	7 November 2016

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Author	Hugh Middlemis Principal Groundwater Engineer, Hydrogeologic	
Version 1:	2 August 2016	Initial draft for review by Supervising Scientist Branch
Version 2:	19 August 2016	Final draft addressing comments from SSB
Version 3:	7 November 2016	Revised wording in s.2.3 bullet #4 to correct misleading inference drawn from Fitton 2015

THIS REPORT SHOULD BE CITED/ATTRIBUTED AS:

Middlemis, H. (2016). Ranger Pit 1 Consolidation Modelling Independent Review. Prepared by Hydrogeologic for Supervising Scientist Branch, Department of Environment. November 2016.

1 Background, Scope and Evidentiary Basis

Energy Resources of Australia Ltd (ERA) owns and operates the Ranger uranium mine, within the Ranger Project Area (RPA). The RPA is located on Aboriginal land and is surrounded by (but separate to) Kakadu National Park. Uranium ore was mined from Ranger Pit 1 until 1994 using conventional open-cut methods. Subsequently, tailings were deposited in Pit 1 between 1996 and 2008, and the Pit 1 (Figure 1) has now been capped with a waste-rock and laterite layer.

Figure 1 - Ranger Pit 1 location (GoogleEarth image captured August 2016)

The Environmental Requirements pertaining to disposal of tailings at Ranger mine state:

> *"Final disposal of tailings must be undertaken, to the satisfaction of the Minister with the advice of the Supervising Scientist on the basis of best available modelling, in such a way as to ensure that:*
>
> *(i) the tailings are physically isolated from the environment for at least 10,000 years;*
>
> *(ii) any contaminants arising from the tailings will not result in any detrimental environmental impacts for at least 10,000 years."*

A range of investigations and modelling studies of Pit 1 tailings disposal and contaminant transport have been undertaken by consultants and/or ERA, culminating in:

- ATC Williams (2012): tailings consolidation model development and scenarios
- Fitton Tailings Consultants (2015): updated and re-ran the consolidation model
- ERA (2016): comprehensive Pit 1 Notification report on the long term tailings consolidation and contaminant transport modelling studies.

The objectives of the tailings consolidation modelling investigations were to estimate the rate and magnitude of tailings consolidation and settlement, the flow of pore water from the tailings that is expressed due to the consolidation process, and the contribution of consolidation flows to total flow from Pit 1.

The Supervising Scientist Branch (SSB) requested a detailed desktop review be undertaken into the consolidation processes and assumptions of the modelling work conducted by ATC Williams and Fitton Tailings Consultants. A key review focus is to assess whether the approach is consistent with current modelling guidelines and can be considered to be representative of national and/or international best practice.

The scope of this independent review comprises:

1. **Formal review of the following reports:**
   a. Fitton 2015 Pit 1 Consolidation review. 28 October 2015. (Appendix C of ERA 2016 Pit 1 Notification. Final in-pit tailings level. 16 March 2016).
   b. ATC Williams (2012). Energy Resources of Australia Ltd, ERA Ranger Integrated Water, Tailings and Closure Pre-Feasibility Study, Draft Report – Pit #1 Updated Consolidation Analysis. December. (Appendix 4 of Fitton 2015)
      i. Note 1: Reference material provided by SSB:
         -ERA 2016 Pit 1 Notification. Final in-pit tailings level. 16 March 2016;
         -OWS Advice 2016-011 Pit 1 Tailings Level;
      ii. Note 2: Additional reference material may be provided upon request throughout the duration of the contract.
2. **Final report detailing the review outcomes**, including assessment of the veracity of the information provided, the appropriateness of assumptions made, and the validity of the outcomes reported. Advice is also sought on:
   a. The level of confidence that can be placed on the values used as model input by ATC Williams and Fitton Tailings Consultants, and generated as model output by Fitton Tailings Consultants;
   b. Recommendations for improving the simulations and predictions; and
   c. Any specific gaps in knowledge or other issues identified during the review.

2 Findings

It is my professional opinion that, while many elements of the Ranger Pit 1 Consolidation Modelling appear to have been well designed and executed, there are also many inconsistencies and/or inadequate justifications for certain assumptions that render the overall study not acceptable in best practice terms, as explored below.

2.1 FITTON (2015) PIT 1 CONSOLIDATION REVIEW

The consolidation modelling itself appears to have been undertaken with fewer inconsistencies and issues of concern than have been identified in relation to the other studies, so this will be discussed first.

The basis for the consolidation modelling is to accept the validity of the ATCW (2012) model and to apply better information to the model based on tailings survey measurements post-June 2013, along with better information on the extent, depth and timing of fill placement. The methodology is appropriate given the acknowledged uncertainties applying prior to 2013 in measuring the volumes (or tonnages) of tailings deposition (errors in order of ±5%) and the tailings surface topology (errors of up to 1.5 m identified in the “average” tailings level).

The consolidation modelling method has been upgraded with improved data quality on deposition and measured settlement from 2013 to 2015, which is a sound approach to validate the model as a predictive tool for the final stages of backfill. Section 5.2 indicates that, at 2015, the computed volume of settlement (199,200 m^3) is within about 10% of the "measured" volume (227,500 m^3), and the computed and average settlements are within 5% (0.78 and 0.74 m). This should be classified as good model performance in relation to improved measurements, and is considered fit for the purpose of the final stages of consolidation and capping (based on the reported data available; more on this later).

Measurement error is a key uncertainty applying to consolidation calculations at Pit 1. Although the volume of Pit 1 (24 Mm^3) is based on accurate pit void surveys, the estimation of tailings infill volumes or tonnages is subject to calculations involving the "measurement" of the tailings surface and/or the density of the tailings, which are subject to considerable uncertainty. The density sampling and testing has generated some of the best quality data available, but even that is a limited data set (e.g. samples from only the upper 20 m of tailings, whereas computed density extends down to 150 m depth; Figures 19-21 of ATCW, 2012). The consolidation model itself comprises algorithms for calculating a balance between the tailings deposition and settlement volumes and the volumes of expressed porewater (although the algorithms are not presented in the reports reviewed, which is not best practice). The deposition and settlement volumes are reasonably constrained by various measurements (although uncertainties remain). However, there are no measurements presented on water balance volumes (e.g. expressed porewater "consolidation flows"), which is a key method used to constrain model calibration and to reduce model non-uniqueness (Barnett et al, 2016).

In this case, there is a fundamental problem that the key elements of the modelling are not well constrained by measurements (especially water balance volumes) and the exact mathematical basis for the algorithms is not presented in the reports reviewed.

The modelling methodology assumes a discrete increment method of fill placement, which results in the calculated "peaky" consolidation flows. However, that is accounted for (appropriately) by integrating the area under the curve to estimate the total flow. The results are described in section 5.3 of Fitton (2015) in terms of average flows, which is appropriate when comparing against other water balance elements, but the lack of presentation/discussion in terms of integrated and/or cumulative volumes is not helpful. It is not clear from the Fitton (2015) report whether the statements of expressed porewater percentages are based on assumptions (or perhaps are rules of thumb derived from interpretations of model results), or are actually results from the consolidation model. For example, section 5.3 states that about 60% of the expressed porewater reports as upwards flow (and thus would be decanted, in which case, one would expect to see volume measurements documented), while section 4.4.2 states that "40-45%" reports as downwards flow (and thus is lost to groundwater, which cannot be measured directly, and thus it remains a fundamental uncertainty).

The uncertainties in measuring the tailings level/volume has necessitated what is effectively a back-calculation (using the consolidation model) of the tailings volume. The result is a 5.3% increase from the reported 25.6 Mt to 26.9 Mt (ATCW, 2012, section 3.3). While this appears to be a reasonable calculation based on the data presented and assumptions involved, there is inconsistent reporting of this volume. For example, Fitton indicates in section 2 that tailings deposition was "approximately 25.6 Mt (±5%)", which actually comprises a range of 24.3 to 26.9 Mt, but the 25.6 Mt value is repeated in ERA (2016) section 1.

There is also an issue regarding the inconsistent reporting of other key volumes, notably that ERA (2016) indicates 3.1 Mm^3 for the volume of expressed tailings porewater (section 1), whereas ATCW (2012) states (in section 3.3) that the 3.1 Mm^3 estimate was revised downwards to 1.4 Mm^3 (a reduction of 55%). The revision downwards was due to the back-calculation by the consolidation model (ATCW 2012, section 3.2) using the 26.9 Mt estimate, the adopted compression curve of Knight Piesold ROM1, and the ATCW (2009) permeability curve. This reportedly gives the best match to the tailings infill period and the "measured" tailings levels, but there is no other supporting justification for the selection of those parameter sets from among the wide range of curves available.

Further, as Fitton (2015) does not mention the calculated volumes (3.1 Mm^3 or 1.4 Mm^3), it is not immediately clear which volume assumption has been applied to the modelling (presumably the 1.4 Mm^3, as Fitton adopted the ATCW 2012 model). It is not clear whether this discrepancy is material to the analysis, partly because the Fitton (2015) and ERA (2016) reports are unhelpful in applying a focus on flow rates and concentrations rather than presenting adequate detail on integrated or cumulative volumes.

If there is, in fact, measurement data available on water balance volumes (e.g. expressed porewater decant volumes), then that should be used in a post-priori model verification process. Such a "blind" verification process (and/or a post-audit in modelling guideline terms; Barnett et al, 2012) uses measured data that has not been used in the model calibration process to verify that the model is indeed a well-constrained predictive tool. If the model results do not conform to the verification data, then a detailed model audit would be required. This involves a detailed review of the conceptualisation/s, algorithm/s and parameterisation/s (and possibly development of alternative conceptualisations and/or algorithms), and an audit of their implementation in the model/digital data sets, before revising the calibration and prediction, and undertaking uncertainty assessments. If the verification process is successful, however, then that would substantially improve confidence in the consolidation model capability and demonstrate reduced influence of uncertainties (but not remove the need for comprehensive uncertainty assessment).

The Fitton (2015) report documentation should be improved to differentiate measurements from calculations, remove inconsistencies and to properly justify key assumptions. For example, the statement in Fitton (2015) section 4.4.1 that "the magnitude of settlement becomes relatively insensitive to fill depth once the depth exceeds about 20 m" is confusing in that it seems illogical and it is not clear whether it relates to the tailings fill depth or the waste rock capping. Further, Figure 4 of ERA (2016) shows that the predicted final tailings level is lowest (i.e. settlement is greatest) over the deepest parts of the pit (thickest tailings), so the statement must presumably apply to the waste rock fill. This is another example of the many inconsistent statements in the reports, which serves to reduce confidence in the results.

Consolidation Review Summary:

In modelling terms, the above issues demonstrate that the consolidation modelling is not very well constrained by measurements (especially on water balance volumes). The key implication is that the consolidation modelling is significantly affected by non-uniqueness and thus it is subject to considerable uncertainty, unless water balance measurements become available (e.g. metered volumes of expressed porewater and/or from the drainage adit dewatering bore) for a successful post-priori verification. A further implication is that significant uncertainties currently apply to the water balance inputs to the contaminant transport modelling.

Having said that, the consolidation model performance is good in relation to improved measurements on tailings levels and settlement from 2013 to 2015, and thus it is considered fit for the purpose (assuming that there are no other measured data to help constrain the model) to inform the final stages of consolidation and capping. Where the limited measurement data is the best available, then best practice in this case would require substantial improvements to the uncertainty assessments, which should be undertaken with the consolidation model and also the solute transport model, consistent with best practice guidelines (Barnett et al, 2012).

2.2 CONCEPTUALISATION

The development of a robust conceptual model is the critical foundation step in any hydrogeological analysis (Barnett et al, 2012; section 3), and in particular:

- the level of detail within the conceptual model should be based on the modelling objectives, the availability of quality data, knowledge of the groundwater system of interest, and its complexity.
- alternative conceptual models should be considered to explore the significance of the uncertainty associated with different views of how the system operates.

The ERA (2016) hydrogeological conceptualisation (Figure 18 of ERA, 2016; presented below as Figure 2) identifies many permeable features between Pit 1 and Corridor Creek, including the "MBL aquifer zone", which is contiguous with a "Pit 1 permeable zone" and a "seepage limiting barrier" (SLB).

Figure 2 - MBL zone conceptualisation (source: ERA, 2016, Figure 18)

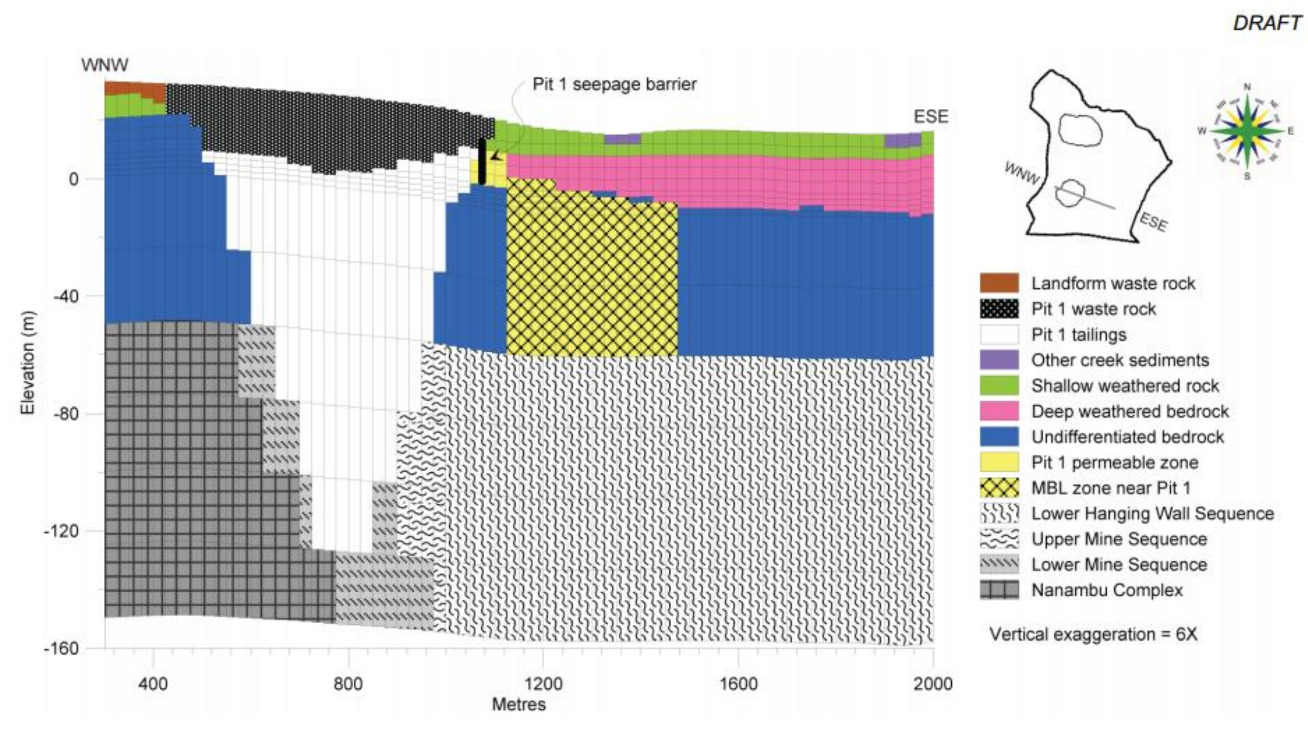

Figure 18: Pit 1 and seepage barrier in cross section through model row 116 (source: INTERA 2014b; Figure 3.5B)

The hydrogeological conceptualisation assumes an effective seepage limiting barrier, although no information is presented to establish its hydraulic properties or how they vary with depth (e.g. is the SLB keyed in to the underlying "undifferentiated basement" and what are the hydrogeological properties of the SLB and that basement?). The report does indicate that the SLB has been breached at least four times when process water was at a level in Pit 1 higher than the groundwater level in the adjacent MBL aquifer (ERA, 2016; section 4.1). The report is deficient in not documenting the levels, as this is a key conceptual concern, in that higher water levels will presumably apply in the long term, given that the Pit 1 system is recharged by rainfall and Corridor Creek forms the discharge zone.

Furthermore, ERA (2016) identifies two existing bores in the MBL area as suitable for monitoring (MB-L and R1C3-1), and states that "there are numerous others (bores) in the area" of the MBL zone. This suggests that the MBL area has been intensively investigated previously, presumably because this was an area that provided inflows to the operational pit that caused dewatering problems. However, no information is presented to adequately detail the hydrogeological conditions that are presumably well known in this area.

No information is presented on the “undifferentiated bedrock” that underlies the SLB and which could form an additional zone of connectivity between Pit 1 and the creek. In addition to the potential for the MBL zone to exhibit potential high hydraulic conductivity (as discussed above), this thin zone (Figure 2) could have been subject to fracture enhancement due to pressure unloading via the pit excavation, and then subsequent re-loading effects as the tailings were deposited and then surcharged with additional fill material.

The following explanation relies largely on a comprehensive compilation of information on pit slope water management (Read and Beale, 2013), but before proceeding, two concepts may need some introduction:

- effective stress is the difference between total stress and pore pressure (total stress is the total pressure formed by the overlying rock (lithostatic) load plus the water (hydrostatic) load).
- hydromechanical (HM) coupling refers to the interdependence of rock properties and their fluid behaviour, via a solid-to-fluid exchange (e.g. a reduction in total stress by pit excavation causing a reduction in fluid pressure) and/or via a fluid-to-solid exchange (e.g. a reduction in pore pressure leading to fracture dilation and increased permeability).

If the total stress is reduced by excavation of rock from the pit for example, the lithostatic unloading can cause a direct HM coupling response as the fractures dilate and/or pore pressures reduce, and an indirect hydromechanical coupling response due to increased aperture (permeability) of the fractures that can change the pressure/flow conditions. The magnitude of deformation from lithostatic unloading depends upon a range of factors (including the weight of material removed and the overall size/depth of the pit), and the effect can extend laterally beyond the pit and vertically below the base of the pit. It is possible that fractures that have dilated due to lithostatic unloading could revert to their initial condition on subsequent re-loading. However, in this case of tailings deposition, there is also the potential for infill of fractures with low permeability tailings material, or possibly smearing (“blinding”) by the tailings of the fracture network exposure in the pit wall. These factors may act in concert with changes in effective stress due to re-loading via tailings deposition causing pore pressure changes, closure of fractures and a decrease in permeability.

These potential conceptualisation issues have not been given adequate consideration in the technical investigations or the risk studies. Once the conceptualisation has been properly considered, it may be deemed necessary to apply a coupled flow-stress modelling methodology, whereby load-induced changes in pressure are accounted for (e.g. using TNO-DIANA or SEEPW-SIGMAW modelling packages). While it is not clear from the reports reviewed the degree to which the consolidation modelling considered flow-stress modelling, the Modflow numerical groundwater modelling package that has been applied in this case definitely cannot account for load-induced effects, only flow-induced changes to pressure (Harrington and Cook, 2011).

Conceptualisation Review Summary:

The hydrogeological conceptualisation is not underpinned with adequate background information (e.g. from dewatering operations), technical justifications for key assumptions (e.g. hydraulic character of the SLB) or sensitivity/uncertainty assessment (e.g. consideration of alternative conceptualisations), and it ignores a potentially significant pit to creek connection through and MBL zone and the SLB. Depending on the validity of the conceptualisation, it may be deemed necessary to apply a coupled flow-stress modelling methodology, whereby load-induced changes in pressure are accounted for directly.

2.3 Pit 1 Water Balance

Whilst a water balance is fundamental to any hydrological investigation or modelling study (Barnett et al, 2012), the modelling studies presented are deficient in that they lack water balance data or even plots of elements of the water balance (other than the calculated consolidation flows of expressed porewater), even though there are references to various water measurement works, including:

- there are several low key references to the MBL aquifer providing inflows and dewatering problems for the operating mine, but no indication of volumes or rates
- ATCW (2012) mentions a vertical dewatering bore that was installed to the drainage adit at the base of Pit 1 (prior to tailings placement) and operated on an intermittent basis (section 2.2)
- Fitton (2015) mentions a Pit 1 flow meter (section 5.3) but it is not known whether this is on the decant system or the dewatering bore, and no data is presented
- Fitton (2015) states in section 2 and section 4.4.2 that some of the water released due to tailings consolidation is “lost to groundwater”. Although such seepage cannot be measured directly (a fundamental uncertainty that has not been explored adequately by the modelling), the other part of that process is the expressed tailings porewater collected via the prefabricated vertical drains (wicks), which reported to decant structures, but no information is presented on the volumes.
- Section 5.3 states that the “measured” consolidation flow is 198 m^3/d, but it does not indicate how or where that measure is obtained. Adopting the “measured” settlement volume of 227,500 m^3 (better described as calculated volume) and an assumed 60% of that comprising expressed (upwards) tailings porewater fluid (over a period of about 700 days from 16 June 2013 to 19 May 2015) generates 194 m^3/d. This suggests that the reported 198 m^3/d value is indeed a model result, and the 60% factor is simply a rule of thumb derived from model results. It is recommended that the “measurement” term should be replaced with “estimated” or “calculated”, and that improved documentation of the assumptions and the calculations involved is warranted in order to meet best practice guidance.
- Despite these problems, the correct conclusions are made in Fitton sections 5 and 6 that the inflow from the “spring” at 8-12 L/s (690-1040 m^3/day) dominates the Pit 1 water balance, although the spring flow estimate is very uncertain (it is not measured).
- The short term rainfall inputs (Fitton, section 6.1) are under-estimated, but this is arguably not critical (given that the spring flow dominates). The 72-hour rainfall event is appropriate (as this maximises the volume of runoff), and while the adoption of a 10-year ARI involves a relatively high probability of occurrence by 2027 (~63%), it also involves a relatively low rainfall intensity (3.8 mm/hr). Rainfall-runoff estimates usually adopt the maximum duration and maximum ARI in order to calculate the maximum volume. In this case, an ARI 100-year event over 72 hours involves 6.3 mm/hour, generating almost twice the volume estimated. In practical terms, the under-estimate of short-term rainfall inputs in Fitton (section 6.1) is arguably not critical, because there appears to be capacity to store the related volumes in the pit. Dealing with the volumes would mean that either it would take up to twice as long (i.e. 20 days) to discharge at the reported rate of 118 L/s, or that higher capacity pumps may need to be applied to the task to achieve the 10-day target. The report does not justify the selection of the ARI 10-year design event, but it does seem a little under-designed. Table 11-11 of ARR (1987) indicates that an ARI 10-year event has ~63% chance of occurrence within a 10-year period, while an ARI 100-year event has ~10% chance of occurrence in 10 years and ~18% chance of occurrence in 20 years.

Best practice modelling requires consideration of all data and especially any data on water balance elements, mainly because that helps address the critical problem of model non-uniqueness (Barnett et al, 2012).

Substantial measurement uncertainties apply to the Pit 1 water balance in the reports reviewed. Measured water balance volumes have high value in constraining model calibration and reducing the potential for model non-uniqueness, and thus reducing uncertainties in the consolidation modelling and the contaminant transport modelling.

2.4 SOLUTE TRANSPORT MODELLING

This review has been completed in relation to only three reports (i.e. without access to all the relevant material). However, some comments are warranted in relation to the very brief summary of the results of the solute transport modelling presented in ERA (2016). Although that work has been independently reviewed, the results presented appear to be quite inconsistent and/or unrealistic, notably regarding the following issues (with reference to ERA (2016) Figures 8-12):

- Figure 8 shows a time series of the predicted mass of Mg released from the waste rock and also the tailings sources that appears to be reasonable except for the substantial decrease in Mg load from the waste rock source immediately after 270 years. This sudden change is not explained (simplistic statements to the effect that the peak occurs at year 270 do not form an explanation, although detailed explanations may be made in other reports not sighted). Figure 9 shows a small section of the plume with concentrations above 100 mg/L present between the pit and the creek at 100 years and still there at 270 years (possibly a little larger, hard to tell with such a small plot; again, not consistent with guidelines). However, by 400 years (i.e. after a shorter subsequent interval of just 130 years), this high concentration sub-plume has dissipated, presumably because the waste rock source load has suddenly decreased post-270 years. The sudden change appears to be completely unrealistic, and although it may be comprehensively analysed in other reports, it is presented here without an indication of the range of uncertainty. Footnote no.11 (section 5.1 of ERA, 2016) does indicate that a conservative approach has been intentionally applied, but that is the only mention of the term "uncertain" or "uncertainty" in the report. At least in terms of presentation, there are deficiencies with the report in relation to best practice guidance, as further explored below.
- Regarding Figures 10 and 12 showing cross-sections of the predicted solute concentrations out to 10,000 years, with Mg concentrations shown in colour-flood distributions (at different scales, which is not helpful and certainly not consistent with guidelines) emanating from the waste rock (Figure 10) and the tailings (Figure 12), the following inconsistencies are apparent but have not been explained:
    - Both plots show the "ground surface", but while Figure 10 shows concentrations up to the ground surface, Figure 12 shows white space below the ground surface.
    - The results appear to show seepage from the waste rock and from the tailings, but the concentrations at the interface of the waste rock with the tailings do not match (between Figures 10 and 12), which is a serious concern. Taking the results at face value, one possible interpretation is that the results were taken from two separate runs (and this was subsequently confirmed), but that is also of concern as the information presented then would not cover a cumulative impacts case (both the waste rock and the tailings combined), which would be a minimum requirement.
    - In each case, the concentration is quite different between Pit 1 and the creek, and particularly in the vicinity of Corridor Creek. Figure 12 also shows the plume extending much further beyond the creek and also to a much greater extent in

the underlying units than is shown in Figure 10. The report is deficient in not presenting plots to clearly document the cumulative impacts cases and allow unambiguous interpretation of the results (i.e. in a manner consistent with the established guidelines).

- Figure 9 shows a plan view of the plume emanating from the waste rock source and connecting with the creek, while Figure 11 shows that the plume from the tailings infill source is not connected to the plume at the creek itself (even though both plan view plots indicate that the results are from “model layer 1”). While this is consistent in principle with the cross-section plots (Figures 10 & 12), Figure 11 clearly shows high concentrations contiguous with the creek (i.e. above 100 mg/L and thus reportedly above background levels), contrary to Figures 9 & 10 (i.e. the issue is that cumulative impacts appear to have not been presented).
- Figure 12 shows the plume emanating from the Pit 1 tailings infill via a seepage pathway over the top of the SLB. In itself this may be appropriate if the actual conditions warrant it, but it does depend on the confirmation of the hydraulic barrier effect of the SLB itself and also of the sound foundation of the SLB into the underlying undifferentiated bedrock, and also of the confirmation that the bedrock itself is very low permeability. The reports do not establish those factors.
- The commentary on Figures 9-12 suggests that the Mg plume concentrations “would not be distinguishable from background groundwater” after about 300 years, but that raises several issues of concern. Firstly, the figures should show the background concentrations in order to establish the point that is made. Secondly, as indicated above re Figure 8, the sudden and unjustified drop in concentration from the waste rock source at year 270 would appear to be the reason why the concentrations decrease beyond 300 years, but this sudden change is not justified in the report reviewed (although it may be justified in other reports not sighted), and its uncertainty range is not presented or discussed. Thirdly, as indicated above, Figure 11 clearly shows high concentrations contiguous with the creek (i.e. above 100 mg/L and thus reportedly above background levels) from 270 years to 10,000 years.
- Taken at face value, the solute transport results appear to confirm the average long term solute loadings and the dilution flow rates required (Tables 6, 7, 8 & 9, and Figure 8). However, there is no data presented on flow in Corridor Creek to justify the conclusions. As a minimum, time series plots or flow duration curves are required to confirm that the 1 m^3/s dilution flow requirement would be easily achieved in practice.

Solute Transport Review Summary:

There are many inconsistencies in the solute transport model results presented in ERA (2016) that warrant a detailed model audit, whether or not a conceptualisation review (refer section 2.2 above) confirms the need for a coupled flow-stress modelling methodology, whereby load-induced changes in pressure are accounted for directly.

3 Summary and Recommendations

This independent review has identified that the consolidation model is not very well constrained by measurements (i.e. in modelling terms, it is significantly affected by non-uniqueness). It is therefore subject to considerable uncertainty, unless water balance measurements become available (e.g. metered volumes of expressed porewater and/or from the drainage adit dewatering bore) for a successful post-priori verification. A further implication is that significant uncertainties currently apply to the water balance inputs to the contaminant transport modelling.

Having said that, the consolidation model performance is good in relation to improved measurements on tailings levels and settlement from 2013 to 2015, and thus it is considered fit for the purpose (assuming that there are no other measured data to help constrain/verify the model) to inform the final stages of consolidation and capping. Ongoing monitoring and measurements are required to provide data to (continue to) verify the model. Where the limited measurement data is the best available, then best practice in this case would require substantial improvements to the uncertainty assessments, which should be undertaken with the consolidation model and also the solute transport model, consistent with best practice guidelines (Barnett et al, 2012).

The report documentation should be improved to differentiate measurements from calculations, remove inconsistencies and to properly justify key assumptions, preferably with data and commentary on hydrogeological conditions during previous investigations (e.g. during mine operations and subsequent tailings infill, especially on the drainage adit dewatering and the expressed porewater volumes). The reports are deficient without water balance data or even plots of water balance elements (other than the calculated consolidation flows of expressed porewater) and the flow-duration character of Corridor Creek (in order to evaluate the dilution flow requirements).

The hydrogeological conceptualisation is not underpinned with adequate background information (e.g. from dewatering operations), technical justifications for key assumptions (e.g. hydraulic character of the SLB) or sensitivity/uncertainty assessment (e.g. consideration of alternative conceptualisations), and it ignores a potentially significant pit to creek connection through and MBL zone and the SLB. Depending on the validity of the conceptualisation, it may be deemed necessary to apply a coupled flow-stress modelling methodology, whereby load-induced changes in pressure are accounted for directly (i.e. Modflow replaced with TNO-DIANA or SEEPW-SIGMAW or similar).

There are many inconsistencies in the solute transport model results that warrant a detailed model audit, and then further modelling to investigate the uncertainties and alternative conceptualisations.

4 References and Declaration

4.1 EVIDENTIARY BASIS FOR INDEPENDENT REVIEW (KEY DOCUMENTS)

ERA (2016). Pit 1 Notification. Final in-pit tailings level. 16 March 2016.

Fitton (2015). Ranger Uranium Mine, Northern Territory. Pit 1, Consolidation Review. Prepared for Energy Resources of Australia Ltd. 28 October 2015. (presented as Appendix C of ERA (2016) Pit 1 Notification. Final in-pit tailings level. 16 March 2016).

ATC Williams (2012). ERA Ranger Integrated Water, Tailings and Closure Pre-Feasibility Study, Draft Report – Pit #1 Updated Consolidation Analysis. Prepared for Energy Resources of Australia Ltd. December 2012. (presented as Appendix 4 of Fitton, 2015).

4.2 GUIDELINES AND OTHER REFERENCES

Australian Rainfall and Runoff (1987). A guide to flood estimation. D.H. Pilgrim (Ed.). Institution of Engineers, Australia.

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A. (2012). Australian Groundwater Modelling Guidelines. Waterlines report 82, National Water Commission, Canberra. URL: http://archive.nwc.gov.au/library/waterlines/82.

Harrington, G.A. and Cook, P.G. (2011). Mechanical loading and unloading of confined aquifers: implications for the assessment of long-term trends in potentiometric levels. Waterlines report series no.51, June 2011. National Water Commission, Canberra.

Read, J. and Beale, G. (eds.) (2013). Guidelines for Evaluating Water in Pit Slope Stability. CSIRO Publishing.

4.3 DECLARATION

For the record, the independent reviewer (Hugh Middlemis) is an engineer and hydrogeologist with more than 35 years' experience, Director/Principal at Hydrogeologic Pty Ltd since 2013. Hugh is an independent modelling specialist with 25 years' experience in this field, including developing models for several projects in the Northern Territory (but not at Ranger), notably including the Woodcutters open pit tailings infill investigations. Hugh is principal author of the MDBA groundwater modelling guidelines (Middlemis et al, 2001) and was awarded a Churchill Fellowship in 2004 to benchmark groundwater modelling against international best practice. Hugh has been appointed to independent review roles by many Australian government agencies, including the (Cwlth) Department of the Environment and also the (NT) Department of Land Resource Management (in both cases since 2014). We note that Hugh Middlemis has not undertaken any work for ERA nor for its consultants investigating Pit 1, nor for any other party relating to the Ranger Uranium Mine in the last ten years. However, we note that Hugh has had limited exposure to investigations at Ranger Pit 3 when he worked at Aquaterra prior to 2010, as part of multi-disciplinary project teams. We believe there are no conflict of interest issues in relation to this review task.

Appendix 5

South Australian Department of Environment, Water and Natural Resources – Pit 1 groundwater and contaminant transport model review: *Review of Contaminant Egress Mitigation Modelling for Ranger Pit 1 Closure*

Preface 25/01/2017

DEWNR provides the following preface for the report Review of Solute Egress Mitigation Modelling for Ranger Pit 1 Closure provided to the Supervising Scientist Branch (SSB) in 2016 for any distribution beyond the SSB.

The DEWNR groundwater review team assisted the Supervising Scientist Branch (SSB) in 2015 and 2016 by reviewing two Ranger pit closure modelling reports. In 2015, the team provided a review of the Ranger Pit 3 (groundwater) closure model. In August 2016, the team provided the attached review of the Pit 1 closure modelling report. It was intended that both reviews were for internal use by SSB and are therefore more concise than for a public document.

The reader must note that since the Pit 1 closure model is an extension of the Pit 3 closure model, both reviews should be considered together.

Since the completion of this report the reviewers have become aware of additional data becoming available. Any application of the model would need to be reviewed against this additional information to make sure the model is of a sound basis and this additional information should be used to extend the model calibration.

The model is not designed to simulate the wider hydrogeological processes and even with the application of this additional data, the application of the model remains limited to quantifying "the amounts and rates (loadings) of both conservative and reactive groundwater constituents of potential concern (CoPC) that will be transported from Pit 1 to surface water receptors".

Review of Solute Egress Mitigation Modelling for Ranger Pit 1 Closure
Date: 19 August 2016

Project team: Daniel Pierce – Project Manager / Senior Hydrogeologist
Juliette Woods – Principal Groundwater Modeller
Carl Purczel – Senior Groundwater Modeller
Kittiya Bushaway – Groundwater Modeller
Kwadwo Osei-Bonsu – Senior Hydrogeologist / Modeller

Department of Environment, Water and Natural Resources (DEWNR), South Australia
Water Science Unit, Science Monitoring and Knowledge (SMK) Branch

Background

Energy Resources of Australia Ltd (ERA) owns and operates the Ranger uranium mine (Ranger) which is situated on the Ranger Project Area (RPA). The RPA is located on Aboriginal land and surrounded by, but separate to, Kakadu National Park.

Uranium ore has been mined from two pits (Pit 1 and Pit 3) using conventional open-cut methods. Mining Pit 1 ceased in 1994 while mining Pit 3 ceased in 2012. The Environmental Requirements pertaining to disposal of tailings at Ranger mine state:

"Final disposal of tailings must be undertaken, to the satisfaction of the Minister with the advice of the Supervising Scientist on the basis of best available modelling, in such a way as to ensure that:
(i) the tailings are physically isolated from the environment for at least 10,000 years;
(ii) any contaminants arising from the tailings will not result in any detrimental environmental impacts for at least 10,000 years."

This stipulates emplacement of tailings and associated wastes into the mine pits, a process that has already commenced. Deposition of tailings in Pit 1 occurred between 1996 and 2008 and the pit has now been capped with a waste-rock and laterite layer.

To enable assessment of environmental risk associated with long-term tailings deposition in the mined-out pits, ERA engaged external consultants (INTERA) to develop a numerical groundwater model that simulates solute transport (egress) from Pit 1.

The Pit 1 closure model is an extension of the Pit 3 closure model which has been previously reviewed by DEWNR. Both the Pit 1 and Pit 3 closure models were constructed and calibrated by INTERA to assess the potential impacts to Magela and Corridor Creeks from closure of Pit 3 and Pit 1 respectively. They are reported on in the following documents:

- *Appendix D Final Report: Solute Egress Modelling for ERA Ranger Pit 1 Closure (15 July 2014)*
- *Final Report: Solute Egress Mitigation Modelling For ERA Ranger Pit 3 Closure (1 July 2014)*
- *Assumptions for Solute Egress Mitigation Modelling for ERA Ranger Pit 3 Closure (undated).*

Additional documentation has been made available by the Supervising Scientist Branch (SSB) to provide supplementary information that relates to the model or model conceptualisation. These being:

- *Pit 1 Notification: Final in-pit tailings level (16 March 2016)*

- *Final report: solute egress modelling for ERA Ranger 3 Deeps mine closure (15 March 2014)*
- *Final report on Ranger mine site Pit#1 Closure Strategies (CSIRO, June 2014)*
- *Seepage Limiting Barrier Pit #1 ERA Ranger mine Detailed Design (URS, April 2005)*
- *Seepage Limiting Barrier Pit #1 ERA Ranger Mine Construction (URS, June 2006)*

SSB requires a detailed desktop review to be undertaken to confirm the hydrogeological processes and assumptions of the modelling work conducted by INTERA. Particularly, whether the modelling approach is consistent with current modelling guidelines and can be considered to be representative of national and/or international best practice.

Scope of Work

In keeping with our recognised expertise, DEWNR groundwater review team have focussed on the numerical groundwater flow and solute transport models. This review concentrates on the modelled closure of Pit 1, however much of the model detail is found in the Pit 3 closure model documentation (Energy Resources of Australia, 2014), including much of model construction, model calibration and discussion. As such, many of the comments made in the DEWNR review of the Pit 3 closure model review are applicable to this review of the Pit 1 closure model. Comments made in this document should be considered alongside those made in the DEWNR review of the Pit 3 closure modelling (DEWNR, 2015).

The review of the modelling approach is based on DEWNR model review guidelines (Yan *et al.*, 2010) and the Australian Groundwater Modelling Guidelines (Barnett *et al.*, 2012). Where no guidelines are available specific comments are made regarding the adequacy or otherwise of the approach used.

Exclusions

As with the review of the Pit 3 closure model, DEWNR is not able to provide comment on certain aspects of INTERA's modelling work. Without further information, the DEWNR groundwater review team is not able to comment on how the model conceptualisation fits with available data from the region, apart from data presented in the report. We are also not able to review the chemistry of the pollutant source and reactive solute modelling (presented previously in the Pit 3 closure report), and recommend that this be reviewed by someone with suitable expertise in uranium hydrogeochemistry.

Findings

The Pit 1 report is well constructed with appropriate level of detail and is presented in a professional manner. The topics covered in the report include:

1. Background and objectives of the studies
2. Hydrogeologic conceptual model for Ranger Mine
3. Sources for solute loading and transport
4. Predictive flow and transport for conservative solutes
5. Summary based on objectives

In addition to these, the Pit 3 report covered the following topics which are relevant to the Pit 1 report:

1. Model construction
2. Calibration of numerical flow model
3. Predictive flow and transport for conservative solutes
4. Predictive flow and transport for reactive solutes

5. The impact of seasonal variation versus steady stresses was tested.

DEWNR's previous review of the Pit 3 report found that a significant amount of site-specific data has been collected and reviewed by INTERA. The data presented are also applicable to the Pit 1 model. The site conceptualisation has been presented with a detailed analysis of the primary hydrogeological processes involved. There is sufficient detail to develop a convincing conceptual hydrogeological model, which forms the basis for the numerical groundwater flow and solute transport modelling.

A predictive flow and transport model was created for the overall Pit 1 modelling. MODFLOW-SURFACT was applied to the flow and transport models.

Overall, the previous review found much of the Pit 3 closure model was sound. This is equally true of the Pit 1 closure model. However, there were some major issues regarding model conceptualisation, design and simulation approaches that were highlighted in the Pit 3 closure model report that are applicable to this body of work. These relate to the regional context (i.e. an area several times larger than the mine site), calibration and sensitivity/uncertainty analysis. Further to these, additional issues have been highlighted that are specific to the Pit 1 model. These issues are described here, and summarised in the Issues Log at the back of this report. There are further relatively minor issues which may be able to be easily resolved, and which we have included in the Issues Log. Minor issues which were identified in the Pit 3 model review that are still relevant to the Pit 1 review have been restated in the Issues Log.

1. *Regional context*

As highlighted in the Pit 3 closure modelling review, the regional context of the underlying model requires some discussion to justify the model domain (both lateral extent and model layering).

The regional scale context was not discussed in either the Pit 1 or Pit 3 closure modelling documentation. Most critically, there is no discussion of the groundwater flow direction within and around the study area, or a potentiometric contour map of the regional water levels. This is required to justify the model domain (both lateral extent and model layering), boundary conditions and initial conditions.

It has been assumed that the groundwater levels return to the natural pre-mining conditions, which serve as the initial conditions in the predictive flow model. Flow model initial conditions need to be consistent with regional potentiometric heads. As with the review of the Pit 3 closure scenario, it is suggested that analysis of the regional groundwater flow should be undertaken to ensure that the initial water levels used as initial conditions in the predictive model are consistent with the regional flow regime. Some presentation of the groundwater potentiometric heads within and outside model domain (including the deeper geological layers) are required to justify initial conditions for the predictive flow model.

Justification should be provided for the deactivation of the model layers representing the deeper bedrock units in the calibration model, and reactivating them in the predictive scenarios. The potential impact of mining operations on these deeper units should be considered.

2. *Calibration*

Calibration performance of the model was raised as a concern in the review of the Pit 3 model (DEWNR, 2015), with modelled water levels generally being a poor match for the observed water level data presented. As the Pit 1 closure prediction utilises the same model, this criticism is equally valid for this prediction model. Similarly, the 1 year calibration period used for the model remains insufficient to confidently predict water levels and transport of solutes over a period of 10,000 years.

Specific to this exercise, the calibration performance of the model at well locations between Pit 1 and Corridor Creek are critical. In many instances, the calibrated water level in these locations is higher than the observed levels. This can be seen in the calibration model hydrographs presented in the INTERA Pit 3 report (Appendix D), specifically observation bores SMP1 – SMP6, CC5A, CC8 CC10, BRA and BRB. The flux between Pit 1 and Corridor Creek is highly dependent on the water level gradient between the two. It is not clear if the gradient has been underestimated; if so, it would contradict the conservative approach that has been adopted in this project. Some analysis is require to verify that the adopted initial water levels do not result in a reduction in flux towards Corridor Creek from Pit 1 than would be expected to occur in reality.

3. Initial conditions

The initial conditions in both the flow and transport predictions require some justification.

It has been assumed that the water levels within the modelled area have returned to (near) pre mining conditions by 2025. Little justification has been given for adopting this assumption, despite INTERA acknowledging that these conditions may take an unknown number of years to develop. A recovery model which includes the cumulative impacts of both Pit 1 and Pit 3 needs to be undertaken to provide confidence that the adopted initial conditions are reasonable.

It has been assumed that the source of solute in Pit 1 at the start of the predictive model (at 2025) is contained entirely within the Pit 1 footprint and that the concentration outside of the pit is zero. This assumption requires justification. Concentration of magnesium in the sampling location OSS, located outside both Pit 1 and Pit 3, indicates levels significantly higher than the assumed initial concentration in the waste rock of 60 mg/L (INTERA Pit 3 report, Table E.2 and Figure E.07), which suggests that the initial distribution of magnesium may be more widespread than assumed.

The background information provided indicates that Pit 1 has been backfilled prior to mining activities ceasing at Pit 3. This has the potential to induce groundwater flow and transport of magnesium from Pit 1 in the direction of Pit 3. By expanding the initial source of magnesium to areas outside of Pit 1, the effectiveness of the Pit 1 seepage barrier may be reduced as additional (and more direct) pathways for magnesium to be transported to Corridor Creek are created.

4. Sensitivity and uncertainty analysis

As highlighted in the previous review of the Pit 3 closure, there is limited sensitivity and uncertainty analysis documented. A more thorough sensitivity and uncertainty analysis would provide support for the choice of model parameters, and provide a range of predictions which are consistent with site information. With specific reference to the Pit 1 closure, the following units were identified as likely pathways for magnesium, those being:

a) The shallow weathered rock,
b) The MBL zone (see comment in Table 2, item 6),
c) The deep weathered bedrock
d) Shear zone at approximately RL3.0 along the southern extent of the barrier, and
e) Rock material at the northern end of the barrier at approximately RL.10.

Additional testing of parameter values on these units would be beneficial and provide a range of scenario results, providing confidence in the model results and the conclusions based upon them.

Parameters within these units that may influence the travel time of magnesium to Corridor Creek that would benefit from sensitivity and uncertainty testing are:

a) Solute transport parameters:
   - Porosity
   - Dispersivity
b) Hydraulic conductivity

Analysis of hydraulic conductivity values undertaken by CSIRO indicates that the parameter values chosen for the model are (approximately) the median of the measured values. While valid, this may not be consistent with the stated goal of producing a conservative model. In this instance, a range of hydraulic conductivity values, bounded by the measured values, should be tested to determine those that maximise the flux to Corridor Creek, and adopting those into the calibration and predictive models.

Evapotranspiration is a critical parameter which should be part of an uncertainty analysis. As reported in the Pit 3 closure report, evaporation flux is a major outflow process in the flow water balance and equals up to one-third of groundwater baseflow flux. Variations in evapotranspiration have the potential to modify the gradient between Pit 1 and Corridor Creek, leading to a change in flux to the creek. Remote sensing data could be used to validate the modelled actual evapotranspiration.

The model may be double-counting evapotranspiration. A precipitation factor was applied to the flow model which varied for different surficial materials: this includes the effects of evaporation as well as surface runoff. The model also implemented the MODFLOW Evapotranspiration (EVT) package; this may overestimate the impact of evaporation in the modelled region.

Variations in climate, taking into account potential long term changes to both rainfall and evapotranspiration should be considered as part of the uncertainty analysis.

It may be useful to consider simulating “best case” and “worst case” scenarios for the prediction scenarios, to illustrate the likely range of possibilities. This may also assist in the design and refinement of a monitoring program for the site.

5. Seepage barriers

Seepage barriers are located within the model domain at both Pit 1 and Pit 3 and are simulated using the MODFLOW horizontal flow barrier (HFB) package. Little information is provided within the provided documentation about the seepage barrier that is located to the south-east of Pit 1, particularly the extent of the barrier. Information regarding the construction and materials used to construct the seepage barrier should be included to justify the conductance value used. Supplementary documentation (URS, 2005 and URS, 2006) was provided to DEWNR regarding the design and construction of the seepage barrier. Information contained within these documents which relate to how the seepage barrier was simulated in this model should be presented, and referenced within this, and the Pit 3, reports. The modelled conductivity values (1×10^{-6} m/d) for the seepage barrier appear to be lower than those specified in the design documentation 8.64×10^{-4}m/d, which contradicts the conservative approach claimed to have been adopted. Justification needs to be given for adopting this lower value.

Given the length of the prediction period (10,000 years), some discussion should be included as to the likelihood of failure of the seepage barrier, and scenario modelling undertaken to investigate the likely impact of failure of the seepage barrier through variation of the adopted conductance value of the seepage barrier. No mention of the longevity of the seepage barrier was given in the supplementary documentation, and so some uncertainty analysis on this aspect would be appropriate.

A range of conductance values could be tested to provide a best and worst case scenario for the effectiveness of the barrier during the 10,000 year predictive period.

Conclusions

The model construction as reported on previously in the Pit 3 closure report provides a solid basis for Pit 1 closure predictions, but requires further work before its results can be accepted.

The regional context must be presented to support underlying calibration model assumptions and the assumed initial conditions of the prediction model.

Cumulative impacts of Pit 1 and Pit 3 should be considered in the calibration model as well as the recovery and predictive models. While this may have been out of scope of the original study, it should be included in a revised model as it may serve to justify the adopted initial conditions (both water level and solute).

The calibration period needs to be expanded to include as much available data as possible, and the match to observed potentiometric heads must be improved. A more thorough sensitivity and uncertainty analysis is needed.

Some consideration should be given to the modelled seepage barrier, and any uncertainty around its effectiveness during the 10,000 year predictive period.

Based on the extensive data collection and analysis presented within the Ranger mine Pit 3 and Pit 1 modelling reports and associated documentation, it is our belief that a high level of confidence can be placed on the parameter values used by INTERA in the development of the Ranger mine model. Conversely, the level of confidence that can be placed in the model results is, by necessity, low. This is driven primarily by the length of the predictive period (10,000 years) compared to the calibration period (1 year). This level of confidence in the model results is decreased further by the issues that have been highlighted in reviews of the model reports for both Pit 1 and Pit 3. Only once these issues are resolved can increased confidence be placed on the model output generated by INTERA.

References

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson. S., Werner, A.D., Knapton, A. And Boronkay, A., (2012) *Australian Groundwater Modelling Guidelines*. National Water Commission, Canberra.

Energy Resources of Australia Ltd, (2014) Final Report: Solute Egress Mitigation Modelling for ERA Ranger Pit 3 Closure, Report prepred by INTRA for ERA.

DEWNR, (2015) Preliminary review of Solute Egress Mitigation Modelling for Ranger Pit 3 Closure.

Yan W, Alcoe D, Morgan L, Li C, and Howles S, (2010) *Protocol for development of numerical groundwater model*, version 1, Report prepared for the Government of South Australia, Department For Water.

Table 1 Log of issues – Major – Identified during either the Pit 1 or Pit 3 reviews.

Item	Topic	MAJOR issue	Comment/Recommendation	Response
1	Model conceptualisation	a. Regional setting is not discussed in the report and no regional potentiometric head maps are presented. b. The impact of the mine on regional potential heads needs to be discussed to justify i) The model domain for the calibration model and ii) Different layering in each of the calibration and scenario models.	Presentation of regional water level maps would justify the choice of model domain and boundary conditions. Some assessment of these regional conditions both before and during mining would provide confidence that the chosen domain and boundaries do not impact the model results. The decision to use significantly different model layer structure should be discussed and justified. There does not appear to be any mention of whether there is any mining activity below -60.5mAHD (base of model layer 10) during the calibration period of 2005-2006.	
2	Calibration	a. Simulation length is not sufficient b. Modelled results are not a good match for the observed values	A one year calibration period is not sufficient for providing confidence in the results of the 10,000 year predictive scenarios. The modelled vs observed water levels do not demonstrate that the model simulates the system to a reasonable level of accuracy.	

Item	Topic	MAJOR issue	Comment/Recommendation	Response
3	Sensitivity and uncertainty analysis	Limited sensitivity and uncertainty analysis appears to have been performed.	Sensitivity and uncertainty analysis should be performed on those parameters that may have a significant impact on the migration of magnesium during the 10,000 year prediction scenario. E.g. a. Porosity b. Dispersivity c. Hydraulic conductivity d. ET e. "Best case" and "worst case A range of possible predictions is recommended.	
4	Uncertainty	Seepage barrier conductance should be subject to uncertainty analysis.	The seepage barrier near Pit 1 is assumed to be effective for the entire 10,000 year prediction period. Justification for this assumption should be provided. Alternatively, a range of conductance values should be tested, representing varying levels of failure of the seepage barrier.	

Table 2 Log of issues – Minor – Identified during the Pit 1 review.

Item	Topic	MINOR issue	Comment/Recommendation	Response
1	Reporting	Location of Pit 1 seepage barrier	Location of the Pit 1 seepage barrier, represented by the MODFLOW HFB package, is not shown in any of the plan view figures. Suggest this should be included on Figure 3.4, and potentially on the hydrolithologic unit figures (Figures A.02–A.05). Additionally, the seepage barrier should be shown extending from layer 2 to layer 5 in the cross sectional figures.	

2	Reporting	Flow analysis	A plot showing flow vectors or pathlines would be of benefit to visualise the local and regional flow patterns and their interaction with the Corridor Creek.	
3	Recovery	No results of a recovery simulation of Pit 1 have been presented.	Backfilling of Pit 1 occurs while mining operations are still active within Pit 3. Potentially, the distribution of solute assumed as the initial conditions to the prediction model in 2025 may be influenced by the mining operations in Pit 3. It is likely that mine dewatering activity in Pit 3 will induce solute migration from Pit 1 towards Pit 3.	
4	Initial Conditions	Initial water level conditions for the prediction model need to be justified.	Initial conditions for the flow model assume that the system has recovered to near natural conditions. Presentation of a recovery model of Pit 1 (and including Pit 3 operations and recovery), preferably validated against observation data would provide justification for this.	
5	Initial Conditions	Initial solute conditions for the prediction model need to be justified.	Initial conditions for the solute transport model assume that the solute source is contained wholly within Pit 1. Justification for this needs to be presented. A contour plot of the current observed magnesium concentrations within the mine and surrounding areas may provide justification for the assumed initial conditions.	
6	Reporting	Undefined acronym	The phrase “MBL aquifer” or “MBL zone” is used in a number of documents. The acronym “MBL” has not been defined.	

Table 3 Log of issues – Minor – Identified during the Pit 3 review (also applies to Pit 1 model).

Item	Topic	MINOR issue	Comment/Recommenadation	Response
1	Model conceptualisation	Representation of Pit 3: a. Seasonally active drain cells b. Inactive cells in interior	Justification of pit representation should be provided. The representation of the pit interior by inactive cells assumes that the perimeter drains are 100% effective at removing any flow that would report to the pit.	
2	Initial conditions	a. Calibration model initial conditions may not consider previous mining activities b. Solute transport initial conditions may not consider potential mixing of groundwater and brine during mine closure and groundwater level recovery	Steady-state conditions should reflect pre-mining conditions, if not, the impact of mining activities prior to the start of the calibration model should be considered The initial conditions of the solute transport model appears to ignore any potential mixing that may occur during the closure and recovery phase of the pit. Potentially, the upper units may have higher concentration of solute than suggested by the initial conditions used.	
		c. Background water /soil chemistry	No baseline chemistry for creek or surface water features and regional groundwater has been presented. Justification of the assumption of zero concentration outside the pit should be included, and some discussion as to whether this is realistic.	
3	Model parameter	a. Potential double-counting of ET b. Validation against remote sensing data	Modelled ET may be overestimated in the model since it is accounted for in the recharge model and the MODFLOW EVT package is implemented. ET could be validated against CMRSET remote sensing data	

4	Model parameter	Porosity	Minimal justification of porosity is provided. Porosity potentially impacts the travel time of solute though advective processes.	
5	Model parameter	Storativity	Further justification for using a storativity value of 1 for model layer 1 needs to be given. Storativity value of 1 is used during the scenario model, which is (effectively) a void parameter. This choice of parameter value may have implications with respect to boundary inflow as the water levels are likely to be under-predicted	
6	Model parameter	Hydraulic conductivity	Comment on hydraulic conductivity of the caps with reference, discussion or justification required.	
7	Boundary conditions	a. Use of GHB for creeks, rather than MODFLOW-RIV package b. GHB water level decreased 2 m after dry period	The reason provided for the use of General Head Boundaries to represent the creeks, rather than the River package is confusing. There is little justification for the decrease in water level in the modelled creeks.	
8	PEST parameters	a. Parameters varied during calibration b. Ranges of values used c. Sensitivity outputs	It is suggested to include documentation of PEST assumptions, parameters and ranges of values used during calibration.	

Appendix 6

DR Jones Environmental Excellence – Mine site geochemistry review: Review of Geochemistry-Related Aspects of Closure Modelling for Ranger Pit 1 and Pit 3

Review of Geochemistry-Related Aspects of Closure Modelling for Ranger Pit #1 and Pit #3

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Report Prepared for:

Office of Water Science & Supervising Scientist Branch - Department of Environment and Energy

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EXECUTIVE SUMMARY

Overview

The Supervising Scientist Branch (SSB) of the Commonwealth Department of the Environment and Energy requires a detailed desktop review to be undertaken of the geochemical processes considered, and assumptions made, by the modelling work conducted by INTERA to predict the egress of chemicals of potential concern (COPC) from Pit #1 and Pit#3 over the 10,000 year period post closure of the Ranger uranium mine.

As requested the two key reports below (including Appendices), plus additional material listed in Section 2 of this review, were reviewed.

a. INTERA 2014. Final report: solute egress modelling for ERA Ranger Pit 1 closure. 15 July 2014 (Appendix D of: ERA 2016 Pit 1 Notification. Final in-pit tailings level. 16 March 2016); and
b. INTERA 2014. Final Report: solute egress mitigation modelling for ERA Ranger Pit 3 Closure. 1 July 2014.

No matters of relevance to the definition of COPC source terms and issues related to the transport of the COPC in the environment were excluded from this review. However, analysis and review from first principles of the complete historical groundwater quality data sets and relevant process water quality records held by ERA were beyond the scope of this review. The review also does not include specific assessment of the flow and transport modelling (ie, geological strata included in the model, element grid and assigned hydraulic parameters), noting that this aspect is being addressed by a parallel consultancy.

Conclusions

- The selection of COPC is consistent with all of the prior work that has been done to identify those solutes most likely to be an issue at Ranger. Although it is not a COPC *per se* Ca needs to be included in the suite of solutes modelled by virtue of its strongly ameliorative effect on Mg toxicity. All COPC have been assumed to be conservative in the solute egress predictions made by INTERA. However, this may not be a valid assumption to use for Ca given its “protective” function. That is, if the concentration of Ca in the discharge is overestimated by virtue of assuming conservative transport, then an unrealistic prediction may be made of environmental significance in relation to the WQ guideline value that is used for Mg.

- The Mg source concentration assigned by INTERA for the vadose zone waste rock backfill is consistent with the existing empirical data set for Type 1 waters (the most relevant). In contrast, the source strength for this zone may have been substantially underestimated for U.

- The use of a geochemical model coupling pyrite oxidation with dissolution of Mg (from chlorite) to predict the length of the time window for elution of above background concentrations of Mg from the waste rock vadose zone should be regarded as indicative only, given the numbers of assumptions that had to be made about initial pyrite content and oxygen concentrations in the backfill.

- It is documented in CSIRO (2014) that secondary minerals are forming within the tailings in Pit #1 as supersaturated phases precipitate. However this appears to be a kinetically slow process with no significant effect thus far in reducing the concentrations of COPC in tailings porewater. Hence it is reasonable to assume that the concentrations of COPC in tailings porewater (and in PTF) will be similar to those currently measured for a long time. There is no indication that concentrations of some COPC might increase through time in tailings porewater.

- The Mg ratio approach to estimating concentrations (and loadings) of COPC discharged from the site through time is appropriate, assuming conservative behaviour for them. However, the predictions may not necessarily be valid given the likely underestimation of some of the contributing source terms.
- The major sensitivity for solute egress from Pit #1 over 1st 50 years will be the amount of PTF that is initially extracted as the tailings consolidates over the first 6 years, including the time required for placement of backfill. Extracting the PTF as it is produced will be the key to ensuring that downstream environmental impact is minimised. It is inferred by ERA in its Notification of Intent (NOI) for Pit #1 closure (ERA 2016) that 99% of the PTF will be removed. This reviewer disagrees with this proposition. In the absence of guidance to the contrary it has been assumed for this review that 90% removal is more realistic.
- The source terms for laterally inflowing groundwater have been underestimated, especially for the shorter term, given the likely presence of waste rock and tailings dam leachates in the up-gradient groundwater flow field. INTERA has assigned country rock (background) COPC values to this source in perpetuity.
- The initial COPC source strength of the saturated zone of waste rock has likely been under-estimated (substantially so for U) as it has been assigned "background" source strength in perpetuity. In practice this rock will contain a pre-existing elevated leachable load that will be eluted through time. This issue is likely to be of most import for Pit#3 given the greater thickness of this layer than for Pit#1.
- The magnitude of the PTF-derived source in Pit#1 may have been significantly underestimated by virtue of a higher transient elevation of the PTF occurring in waste rock, compared with the model assumption that the final elevation corresponding to a given % removal is the starting point for the model. This is an issue since the PTF-wetted material will retain a significant proportion of the PTF solute load, despite subsequent drain down to the target removal level.
- The predicted peak load of 30,000 kg/y of Mg from the Pit#1 is substantially lower than the 203,000 kg/y on average (ERA 2016) that currently leaves the site. Hence it could appear that this load will not be an issue given that no detrimental downstream impact has been detected for the current annual loading of Mg. This conclusion would still be reached even if the predicted peak Mg loads have been underestimated by 50%. However, this 1st pass analysis does not take into account the higher Mg:Ca ratio in tailings-derived water and the fact that the current Mg ecotox guideline for chronic exposure is based on the much lower Mg:Ca ratio under the current operational condition. This aspect may require further consideration by SSB in its assessment of ERA's NOI (ERA 2016) for the closure of Pit #1.
- Reference to Figure 4 shows that the combined effects through time of Pits 1 and 3 need to be considered. Simple addition of the predicted Mg loads from each pit through time provides a reasonable first pass basis for doing this. Running a combined Pits model would probably not provide much more insight. However, in this context it appears that the pre-existing (impacted) solute loads in groundwater in the areas between the domains defined by the pit footprints may not have been taken into account by the model. There will also be a substantial amount of waste rock remaining on the surface after the pits are

backfilled. The contribution of this solute source to annual loads of Mg leaving the site may not have been adequately addressed by the model, and could be significant.

Recommendations

- Given the limited time available this reviewer has not been able to look in detail at the source strength assigned to waste rock for COPC other than Mg, U and Mn. It is recommended that a similar comparison as has been done in this review for Mg, Mn and U is done between the Type 1 and Type 2 water quality datasets for the other COPC, noting that nitrate from blasting residues is more likely to be present in higher concentrations in Type 1 water.
- The effect on initial solute loads of not assuming background starting concentrations for COPC in saturated waste rock and in shallow groundwater should be quantified to determine if this is a significant omission in the predicted loads of COPC in the 50 years after pit backfill has been completed.
- The potential for a much higher Mg:Ca ratio in solute egress from Pit#1 over the initial decades post backfill should be assessed, noting that it may not be appropriate to assume conservative behaviour for Ca given its ameliorative effect on Mg toxicity.
- Transient modelling should be conducted to investigate the sensitivity of PTF rise in PIT #1 backfill to possible management scenarios (eg rate of removal lagging behind rate of production).
- For Pit #1 the model should be run on a monthly time step for say the first 40y to identify if there are likely to be any critical stress periods for solute egress during the annual seasonal cycle, when PTF is the dominant source of COPC. This is especially important because the annual pulse release of solutes from the pit is likely to be offset somewhat from the current situation where solute egress from the site is dominated by within wet season seepage and runoff from above grade waste rock stockpiles.
- Long term average values should not be used for comparative assessment over the whole 10000y time period as this strongly weights the result to the lower loads at longer times. The time window for peak loads should be used as the basis for post closure performance assessment since this will be the critical stress point for assessing the likelihood of success. In particular three time windows should be used for each pit, based on the time series predictions shown in Figure 4.
  - **For Pit #1:**
    - 0-50y for PTF efflux
    - 50-300 y for waste rock leachate
    - 300-10000 y for long term contribution
  - **For Pit #3:**
    - 0-10y for initial condition
    - 10-300 y for waste rock leachate
    - 300-10000 y for long term contribution
- The combined annual loading through time of Mg from Pits #1 and #3 plus the other potentially substantial contributions (eg surface waste rock and rehabilitated tailings dam footprint) to solute exports from the site need to be considered when comparisons are being made with current annual loads of Mg.

CONTENTS

1. INTRODUCTION

1.1 Background

The Environmental Requirements pertaining to disposal of tailings at Ranger mine state:

"*Final disposal of tailings must be undertaken, to the satisfaction of the Minister with the advice of the Supervising Scientist on the basis of best available modelling, in such a way as to ensure that:*

(i) the tailings are physically isolated from the environment for at least 10,000 years;

(ii) *any contaminants arising from the tailings will not result in any detrimental environmental impacts for at least 10,000 years.*"

To meet the first requirement all tailings and associated wastes will ultimately be placed into the two mined-out pits. Deposition of tailings in Pit 1 occurred between 1996 and 2008 and the pit has now been capped with a waste-rock and laterite layer. Deposition of tailings in Pit 3 commenced in 2015 and will continue until all tailings have been transferred to the pit.

To enable assessment of environmental risk associated with long-term tailings deposition in the mined-out pits, ERA engaged an external consultant (INTERA) to develop 3D numerical groundwater models that simulate solute transport (egress) from each of the pits. The overall objective of the numerical groundwater models was to quantify the amounts and rates (loadings) of both conservative and reactive groundwater constituents of potential concern (COPC) that will be transported from each pit to surface water receptors.

The Supervising Scientist Branch (SSB) of the Commonwealth Department of the Environment required a detailed desktop review to be undertaken of the geochemical processes considered, and assumptions made, by the modelling work conducted by INTERA.

1.2 Scope of the Review

The request for quote (RFQ) for this review specified that review be undertaken of the content of two key reports below , plus supporting documentation as required.

a. INTERA 2014. Final report: solute egress modelling for ERA Ranger Pit 1 closure. 15 July 2014 (Appendix D of: ERA 2016 Pit 1 Notification. Final in-pit tailings level. 16 March 2016); and
b. INTERA 2014. Final Report: solute egress mitigation modelling for ERA Ranger Pit 3 Closure. 1 July 2014.

1.3 Exclusions from the Review

No matters of relevance to the definition of COPC source terms and geochemical issues related to the transport of the COPC in the environment were excluded from this review. However, analysis and review from first principles of the complete historical groundwater quality data sets and relevant process water quality records held by ERA were beyond the scope of this review.

The review also does not include specific assessment of the flow and transport modelling (ie, geological strata included in the model, element grid and assigned hydraulic parameters), noting that this aspect is being addressed by a parallel consultancy.

2. DOCUMENTS REVIEWED

CSIRO (2014) Report on Ranger Minesite Pit#1 Closure Straegies. Turner. JV, Byrne J, Davis JA, Douglas GB, Kavianni NN, Kent D, Park J, Prommer H, Shackelton, M, Trefry MG, and Wending L. Mineral Down Under report number EP135637, 545pp.

ERA (2016) Pit 1 Notification. Final in-pit tailings level. 16 March 2016.

Esslemont (2015) Background Constituents of Potential Concern in Groundwater of the Ranger Project Area. 15 April 2015.

INTERA (2014a) Final report: solute egress modelling for ERA Ranger Pit 1 closure. 15 July 2014 (Appendix D of: ERA 2016 Pit 1 Notification. Final in-pit tailings level. 16 March 2016.

INTERA (2014b) Final Report: solute egress mitigation modelling for ERA Ranger Pit 3 Closure. 1 July 2014, plus associated Appendices.

OWS Advice 2016-011. Pit 1 Tailings Level.

SA DEWNR (2015) Preliminary review of Solute Egress Mitigation Modelling for Ranger Pit 3 Closure. 18 Sept 2015;

Smith (2016) Peer review of solute egress modelling. Ranger Pit 1 closure. (Appendix E of ERA 2016 Pit 1 Notification. Final in-pit tailings level. 16 March 2016).

3. GEOCHEMICAL SOURCE TERMS IN PITS

3.1 Overview

There will be three significant contributions to the egress of solutes from both of the capped pits:

- high salinity pore water from tailings
- Pit Tailings Flux (PTF) - leachate produced by upward expression of tailings pore water driven by downward pressure of overlying waste rock; and
- leachate produced by percolation of rainwater through the waste rock cap.

In addition for Pit #3 there is highly concentrated brine that is being injected into the base of the waste rock platform constructed to support the overlying tailings layer. This brine is being produced from the treatment of process water and expressed tailings pore water in a brine concentrator unit.

The composite source term that has been used for solute transport modelling from the pits will be a combination of these sources, the proportions of which will be different for Pit#1 and Pit#3. It will be critical to ascertain how INTERA has apportioned these contributions, as this process will define the concentrations of the CoPC used to drive the solute transport component of the model.

In addition, there is a fourth term that needs to be included in a solute source model for the site. This is the “background” solute contribution from pore water present in the country rocks undisturbed by mining.

3.2 Contaminants of Potential Concern (COPC)

The reviewer agrees with the list of COPC identified by INTERA and predecessors. However, although not a COPC *per se*, Ca is a very important solute that should be addressed as part of the assessment given the strong ameliorative function that Ca has played for Mg toxicity during the operational period of the mine (van Dam et al, 2010). Leachate from waste rock has a very different Mg:Ca ratio than tailings-derived porewater so the change in dominant contributions to solute flux through time needs to be considered in this context, especially re the predicted dominant contribution of PTF to solute egress Pit #1 over the 1^{st} 50 years.

The current assessment has looked at Mg alone through time and has not considered the potential effects of changing Mg:Ca ratio on the receiving environment. The current Mg:Ca mass ratio measured at the MG009 downstream surface water compliance site is <<9:1 (generally <4). Under these conditions the ecotoxicological-derived chronic exposure limit concentration for Mg is 2.5 mg/L (van Dam et al, 2010). However, for Mg:Ca >9:1, noting that the Mg:Ca ratio in tailings pore water is ~10:1, the corresponding limit value for Mg is 0.8 mg/L. This issue is of especial importance when the average concentrations or annual loads of Mg are being compared with the current condition, to infer likely lack of environmental significance for exports of Mg from the site post closure (see Table 8 ERA 2016). Use of the higher limit value for Mg under future conditions where the lower limit might apply could result in an overly optimistic prediction.

The Mg/Ca ratio will be especially important to address during the first 50y when PTF will dominate the egress of solutes from Pit #1 (see further discussion below).

3.3 Geochemical Source Terms

Leachate from Waste Rock Vadose (variably saturated) Surface Zone

Specifying source concentrations for COPC

This component will be produced by leaching of solutes from low grade waste rock. INTERA have estimated the likely composition of this source using both empirical (all COPC) and predictive (Mg) approaches. Table 1 below compiles the source terms assigned by INTERA to the vadose and saturated waste rock zones in the pit backfill. Reference is made to this table in the following discussion.

Table 1: Model source terms for COPC in waste rock backfill (adapted from Table 4.5, INTERA 2014b)

COPC	Units of Concentration	Vadose Zone	Saturated Zone
Magnesium	mg/L	320	60
Uranium		0.5	0.009
Manganese		1.2	0.046
TAN [1]		0.14	
Nitrate-N		0.48	
Total-P		0.06	
^{210}Po	MBq/L	No data	
^{226}Ra		800	89

[1]Total ammonia nitrogen

The empirical approach for deriving the source concentrations of COPC uses water quality data records for bores and/or seepage that are considered to best represent the quality of leachate produced by percolation of rainwater through low grade waste rock (Appendix E, Tables E1 and E2, INTERA 2014b). It is noted that the period of record for some of these data sets (eg CB1 to CB5) is only 1-2 years to 2012. These sources may only have been sampled for this period, although it is possible that sampling has continued beyond the time when the data were initially supplied to INTERA.

According to INTERA, "the empirical approach was based on the assumption that geochemical conditions in the stockpiles should be closely analogous to conditions that will exist in the pits once these same rocks are placed in the pits". This reviewer agrees that such a field-based empirical approach is the most appropriate to define initial (conservative) bounding conditions for leachate to be produced over the intermediate term from fresh waste rock. Concentrations in leachate from such rock would be expected to decline over the very long term following wash out of initially soluble salts and depletion of other source terms (oxidation of pyrite in the vadose zone.

However, only a brief summary of the findings from the analysis of these field data is provided in INTERA 2014b. Given the importance of the waste rock source to the solute load it is unfortunate that no table was provided that contained descriptive summary statistics of the data compiled in Appendix E. In fact there is an internal contradiction in the report on this important matter. In section 4.2.1.1 (Waste Rock and Water Types, INTERA 2014b, p40) three water types are identified based on the results from the review of data compiled in Appendix E of the report:

Type 1 comprises mixture of seepage/runoff from 1s (primarily) and other (2s/3s) rock stockpiles.

Type 2 refers to ground waters from bores screened in rock below stockpiles

Type 3 comprises ground waters from bores screened in stockpiles

Specifically it was stated that "*Most Type 2 waters are Mg-Na-HCO3-type solutions which appear to represent undisturbed ground waters in the Ranger area. Some of these waters later evolve into Mg-SO4 solutions possibly as a result of groundwater displacement by seepage from overlying waste rock stockpiles.*" There is even less clarity in the description of Type 3 waters. Comment was made that "*because seasonal evaporation/dilution effects can obscure changes in water chemistry (for Type 1 waters) caused by water-rock interactions, seepage/runoff samples may not be representative for the purposes of estimating source term concentrations*". Further that "*this conclusion is based on the assumption that solutions migrating in ground waters from within Pit #3 are unlikely to be impacted by these seasonal effects*".

In the opinion of this reviewer this is a very subjective reason for choosing not to use the large dataset (265 points for the Type 1 sources specifically listed in section 4.2.1.1) for Type 1 waters as part of the basis for framing the input solute source terms for the model. In fact the vadose zone of the backfilled rock will be subject to such seasonal variation.

In Section 4.5.2 (Vadose Zone Waste Rock) (INTERA 2014b) it is stated: " *A review of the data for Type 2 and Type 3 ground waters with Mg <320 mg/L revealed that the maximum values for U, Mn, and Ra-226 are approximately 0.5 mg/L, 1.2 mg/L and 800 mBq/L, respectively"*. Subsequently these values were assigned to the composition of water from the vadose zone (Table 4.5, INTERA 2014b). It is noted by this reviewer that the assignment of a 320 mg/L cutoff appeared to be somewhat arbitrary and not definitively supported by analysis of the data (see further discussion of this aspect below)

In the INTERA report for Pit#1 (INTERA 2014a) it is specifically stated that: *"Geochemical analyses of samples from bores that represent undisturbed ground waters in the Ranger area were used as the basis for determining source concentrations for the saturated waste rock backfill in Pit 1"*. Presumably a similar approach was used for the modelling of Pit#3 given that the same waste rock source terms were used for both pits. While it might be "OK" to assume a return to near background concentrations of COPC after several pore volumes have passed through the backfill that is initially loaded with leachable solute, it is not acceptable to assign this condition from the start. In this reviewer's opinion this assumption will result in a substantial underestimation of the initial source term for the "saturated" zone, which accounts for a very large percentage of the total mass of backfilled waste rock.

Given the apparent less than rigorous approach by INTERA to this issue the reviewer converted Table E2 in INTERA 2014b into spreadsheet format and excerpted the relevant Type 1 and Type 2 datasets. The Type 1 sources listed in section 4.2.1.1 (CB1, CB3, CB4, CB5, CB6 NWP1S OSS, TSD1, TSD2, TSD3) were used. In the case of the Type 2 sources the data set was culled to remove those sources that were clearly background and/or the front end of the time series that represented the time before the arrival of a putative seepage front. The summary statistics for the Type 1 and Type 2 datasets are compiled below in Tables 2 and 3.

Table 2: Summary statistics for Type 1 waters (265 sample points)

Metric	Ca mg/L	Mg mg/L	HCO_3 mg/L	SO_4 mg/L	Mn (µg/L)	U (µg/L)	Mg/Ca	SO_4/Mg
Min	3.50	13.30	8.00	62.70	0.20	5.00	0.82	3.71
Max	164	684	199	2614	495	6770	11.6	5.98
Mean	***65.35***	***242***	***81***	***1094***	***50***	***1360***	***3.81***	***4.60***
Stdev	36.25	141	49	618	76	1726	1.59	0.34
60th %ile	64.50	271	84	1240	39	826	3.77	4.66
80th %ile	***93.84***	***361***	***130***	***1642***	***77***	***2506***	***4.68***	***4.83***
90th %ile	120	412	161	1936	118	4592	5.85	4.97

Table 3: Summary statistics for reduced data set for Type 2 waters (374 sample points)

Metric	Ca mg/L	Mg mg/L	HCO_3 mg/L	SO_4 mg/L	Mn (µg/L)	U (µg/L)	Mg/Ca	SO_4/Mg
Min	4	40.6	23.7	30.8	1	0.1	1.3	1.80
Max	397	911	573	4662	2385	783	504	17.36
Mean	***47.0***	***178***	***246***	***682***	***328***	***220***	***60***	***9.02***
Stdev	91.2	183	131	1007	345	155	85	3.90
60th %ile	12.52	120	236	383	353	235	41	9.97
80th %ile	***30.9***	***219***	***316***	***915***	***529***	***363***	***119***	***11.92***
90th %ile	179.2	378	474	1882	670	393	173	13.50

Reference to the Mg:Ca concentration ratio in Tables 2 and 3 shows that the mean and the 80th percentile Mg:Ca ratios for the Type 1 sources are very close to the annual ratio of about 4 that is currently measured at the downstream Magela MG009 surface water monitoring point. In contrast, the ratio for the Type 2 water is two orders of magnitude higher. This is much higher than for process water (ratio of approximately 10) and suggests that Type 1 waters produced from the waste rock stockpiles provide a much better representation of the current seepage and runoff that is contributing to solute egress from the site. This is the same material that will be used to backfill the pits.

The second point to note in Table 3 is that the SO_4:Mg ratio for Type 2 water is much higher than seepage from the stockpiles, suggesting that this is not typical of seepage/leachate from a variably saturated waste rock source. On both of these measures (Mg:Ca and SO_4:Mg) Type 2 waters are not typical of what would be expected from the vadose zone of backfilled waste rock. Hence this reviewer questions the use of Type 2 waters to derive the model COPC source terms for waste rock.

The 80th percentile value for a water quality parameter is typically used for comparison with relevant environmental guidelines (ANZECC and ARMCANZ 2000). By analogy it is proposed here that the 80th percentile values from Table 2 be considered to define the source terms.

The concentration of Mg used for the solute source term is the most fundamentally important value. This is because Mg is considered to be chemically conservative and hence provide a reference for scaling the behaviour of all other solutes – assuming that they too behave conservatively. A waste rock source concentration of 320 mg/L was defined by INTERA (Table 1 above) for Mg in the vadose zone of the waste rock backfill. This concentration is certainly below the highest band of values reported for Type 1 waste rock leachate sources in Table E.2. The statistical basis for assigning this value was not provided by INTERA, with the only relevant comment being that the Type 1 peak values in Table E2 were most probably the result of evaporative concentration in the dry season and hence unreasonably high. However, it is comparable with the 360 mg/L 80th percentile value in Table 2. Hence this reviewer is satisfied that the Mg source term used for the vadose zone of waste rock backfill in the model has not been substantially underestimated.

INTERA (2014b) assigned a maximum value of 500 μg/L for U based on the distribution of data for Type 2 water. This is reasonably consistent with the 80th percentile value of 363 μg/L in Table 2. However, reference to Table 1 shows that the 80th percentile value for Type 1 water is 2506 μg/L, with the mean being 1360 μg/L. This suggests that the source strength for U has been substantially underestimated.

In contrast to U, the 80th percentile concentration for Mn is almost an order of magnitude higher for Type 2 water. Indeed the Mn source concentration of 1200 μg/L assigned by INTERA is just over double that of the Type 2 80th percentile value. It is possible that the higher concentration of Mn found in the Type 2 water is as a result of chemically reducing conditions in the saturated zone at depth. In this context it should be noted that chemical reduction was ruled out (INTERA 2014b) as being a significant geochemical attenuation process for U.

Given the time available this reviewer has not been able to look in detail at the source strength assigned to waste rock for the other COPC. It is stated in section 4.5.1 of INTERA 2014b that Type 2 ground waters were used to define the mean source concentrations of total ammonia nitrogen (TAN), nitrate-N and total-P (values compiled in Table 1 above). However, it is recommended that a similar comparison is done between the Type 1 and Type 2 datasets, noting that nitrate from blasting residues is more likely to be present in significant concentrations in Type 1 water.

Other approaches for estimating concentrations of COPC

It is worth commenting further here on other approaches that have been used to infer the Mg source term in leachate from waste rock. CSIRO (CSIRO 2014) considered that it was inappropriate to use empirical field data to infer the composition of leachate since some of the surfaces of the waste rock dumps had been used for disposal of water from RP2. However, since RP2 is actually the containment for leachate from waste rock over much of the site then the validity of this argument is questionable. In any case, irrespective of origin, solutes that are present in waste rock used for capping must be included in the source term.

CSIRO used Mg source data produced by 400d duration batch leach contact tests. These tests used large pieces of rock in stirred beakers (Figure 1 below). In the reviewer's opinion such a configuration (high water volume and relatively low surface to volume ratio of the large particles) is likely to substantially underestimate the concentration of solutes in leachate from a waste rock stockpile. Attempting to scale from such batch test work to the conditions pertaining at full scale is fraught with problems. Investigations of mass/unit weight of leachable solutes as a function of particle size is needed (at a minimum) to place once off batch leach work into context.

Figure 6.3.1. Detail of experiment #14 (Fresh chloritic schist incubated in RPW/Rainwater) with rock samples stacked on a purpose-built perforated Teflon stand to facilitate fluid circulation. Note also the presence of lighter secondary precipitates on horizontal rock surfaces.

Figure 1: Batch leaching of waste rock from CSIRO 2014.

Duration of solute leaching

The duration for the peak concentration of solute from leaching of waste rock in the vadose (variably unsaturated and aerobic) zone was set at 300y in the model. This duration was predicted by the geochemical model constructed to infer the time required to oxidise the low levels of pyrite present in the waste rock. The pyrite oxidises to release acidity and sulfate, with the acidity being consumed by reaction with the dominant mineral chlorite. Soluble magnesium is a product of this latter reaction. Given the assumptions and uncertainties (including initial pyrite content and oxygen concentration profile in the vadose zone) made in the construction of the model this estimated duration has a very high level of uncertainty as does the peak concentration itself.

Summary of vadose zone source terms

The Mg source concentration assigned by INTERA for the vadose zone waste rock backfill is consistent with the existing empirical data set for Type 1 waters (the most relevant). In contrast, the source strength for U appears to have been substantially underestimated. The higher Mn source strength (than indicated in Table 2) assigned to Mn by INTERA is appropriate given the likely higher mobility of Mn under reducing conditions.

In summary the empirical approach used by INTERA, complemented by geochemical reaction modelling to estimate duration of the Mg pulse produced as a result of pyrite oxidation, is the most practicable way to derive source terms given all of the uncertainties that are involved in estimating the Mg source term from waste rock. However, it is recommended that Type 1 rather than Type 2 waters be used to define the source terms.

Leachate from Waste Rock Saturated (basal) Zone

Waste rock that lies at the base of the capping backfill will ultimately be saturated as a result of the rising groundwater table. In the case of Pit #1 the source of this saturation will be rainwater infiltration from above, lateral flow of groundwater and PTF from below. The “final” position of the interface between “cleaner” overlying water and PTF-impacted water will depend on the balance between how rapidly the PTF is expressed from the wick drains (driven by vertical consolidation caused by the backfill loading) and the rate and ultimate extent of withdrawal of this expressed water via the decant towers. The sensitivities of the extent of PTF rise for predicting solute egress were much better addressed by CSIRO (CSIRO 2014) than by INTERA (INTERA 2014a).

There are two categories of PTF-impacted water that need to be considered. Firstly, the 100% PTF water that has been modelled by INTERA as a “pond” sitting on top of the interface between the tailings and waste rock. Secondly, an overlying transition zone of PTF-impacted water. This transition zone can be defined as the interval between the top (ie the “final” position when withdrawal of PTF water has ceased) of the PTF pond and the maximum height that PTF penetrated into the overlying backfill as consolidation occurs. Essentially this transition zone will be comprised of rock that has been wetted up by PTF, but for which the void volume has subsequently been drained as the PTF water is drawn down by extraction from the decant towers. The PTF-wetted rock is likely to retain a significant proportion (on wetted surfaces) of the PTF COPC that will be able to be subsequently leached by infiltrating rain water and lateral groundwater flow. It will be this potential wetting and draining cycle that will be a much more powerful contributor to define the width of the transition zone than will be upward diffusion against a strong density gradient. This aspect is discussed further in Pit#1 Solute Source Terms in Section 4 of this review.

For Pit#3 the final position of the groundwater table will be determined by rainwater infiltration from above, lateral flow of groundwater, and downgradient drainage. For Pit#3 the influence of tailings porewater on the overlying backfill will be very much less than for Pit# 1 given that the tailings will already be pre-consolidated with little further vertical expression of PTF to occur following backfill.

Pyrite contained in waste rock that lies in the saturated zone will not oxidise. Hence this specific component of the intermediate duration source term for Mg will not be present for waste rock in the saturated zone. INTERA made the assumption that since this was the case then the saturated waste rock zone could be assigned the same background Mg source strength (ie 60 mg/L) as present in country rock unimpacted by mining. Whilst this might be the case over the very long term when the initially soluble reservoir of salts present in the placed rock has been washed out, it will certainly not be the case initially. Hence it is concluded that the initial contribution of the source term from saturated waste rock has been underestimated.

Source terms for the other COPC also need to be assigned for the higher elevation of backfill that has not been contacted by PTF in Pit#1, but which will ultimately lie below the recovered (driven by rainwater infiltration and lateral groundwater inflows and outflows) water table. The COPC source terms for this layer will also need to be assigned for Pit#3. In common with Mg, “background” concentrations have been assigned by INTERA. This is clearly not appropriate for the starting condition given that the rock in the backfill zone will initially contain elevated concentrations of leachable solutes.

For both pits the predicted initial flux of solutes from the “saturated” layer will be much higher than if it is assumed that background concentrations prevail in the pore water from the start of the model run. Detailed comment has already been made above for Mg. However, the situation appears to be especially acute for U where a concentration value of only 9 µg/L has been assumed in the saturated zone. Based on the data in Table 2 this could be underestimating the initial source strength by at least 2 orders of magnitude. It is also worth noting that CSIRO (CSIRO 2014) concluded that insolubilisation of U by reduction of U^{6+} to U^{4+} under low oxygen conditions in the saturated zone is unlikely to be a significant geochemical attenuation pathway.

Tailings Porewater and Pit Tailings Flux (PTF)

In contrast to the leachate from waste rock, the initial concentrations of solutes present in tailings pore water are very well defined by the relatively recent data set obtained from cores extracted from the top 50m or so of the Pit#1 tailings profile (CSIRO 2014). This is the zone that will contribute both to the initial PTF and to the longer term egress of solutes at depth in the tailings. This reviewer agrees that the use of the 87.4 quantile (ie percentile) of the data set is appropriate to define the composition of the tailings porewater and PTF source terms. This is because the 87.4 quantile is even higher than the 80^{th} percentile that is usually used as the basis for delimiting water quality data for environmental assessments (ANZECC and ARMCANZ 2000).

It is documented in CSIRO (2014) that secondary minerals are forming within the tailings as supersaturated phases precipitate. However this appears to be a kinetically slow process with no significant effect thus far in reducing the concentrations of COPC in tailings porewater. Hence it is reasonable to assume that the concentrations of COPC in tailings porewater (and in PTF) will be similar to those currently measured for a long time. There is no indication that concentrations of some COPC might increase through time in tailings porewater.

Brine Concentrate

The data used to define the composition of this source is soundly based on operational data from the brine concentrator.

Background Groundwater

The approach used to define background concentrations of solutes in country rock by INTERA and prior consultants (see Esselmont 2015) is appropriate. This will be the solute source in perpetuity for groundwater flowing through the pit. However, while it is appropriate to use such background concentrations for simulation of water quality in the long term this reviewer questions whether it is a valid assumption for the short to intermediate term. There are two reasons for this.

> (1). The pit was acting as a sink for groundwater over a long time period, and contributions to recharge of this groundwater include leachate from the waste rock stockpiles located around the high side of the pit perimeter plus seepage from the base of the above grade tailings dam. Thus the concentrations of solutes in the groundwater that will initially flow laterally into the surface zone of the waste rock capping may be much higher than have been used in the model.
>
> (2). The model does not appear to have explicitly considered the broader post surface geochemical landscape extending out from the pit perimeter as a solute source term, with similar leaching characteristics as the vadose zone in the rock used for pit backfill. There will be substantial amounts of waste rock remaining in the surface landscape around the higher side of the capped pit and this will continue to contribute leachable solutes, both to shallow groundwater flux to the pit and elsewhere in the landscape. In addition the rehabilitated footprint of the tailings dam may also contribute a flux of solutes that needs to be addressed.

Proportions of the solute sources in (1) and (2) above will enter the back-filled pit, and also contribute directly to the flux of solutes reporting to the Corridor Creek axis. Hence this reviewer believes that these solute sources terms have been substantially underestimated in the short to intermediate (say 10-100y) time frame

Other Potential In-Pit Sources of COPC

As decommissioning of the site progresses the process plant will be demolished and much of it plus other equipment (eg truck bodies) is likely to end up as a component of backfill in the upper horizons of Pit #3. There are two issues that need to be considered.

If the volume of the demolition waste is substantial, and it occupies a laterally extensive horizon, then it is possible that it could influence the assumed parameters of hydraulic conductivity used in the modelling and thus affect predicted times of travel for COPC. The only potential effect on geochemical sources terms could be for ^{226}Ra. ^{226}Ra preferentially accumulates in gypsum which forms concretions on the inside of pipework in the process plant. Thus pipework disposed in the pit is likely to represent a point source of elevated ^{226}Ra. However, the amount of this material may not be significant in the context of the overall loading of Ra in the waste rock backfill. Moreover, $RaSO_4$ is very insoluble.

On balance it is not considered that plant and equipment are likely to represent a significant source of mobile COPC in the pit backfill. However, care will need to be taken to ensure that the method of placement does not result in higher conductivity lateral flow pathways than would occur in the waste rock backfill alone.

4. PREDICTED SOLUTE EGRESS

4.1 Pit #1

Overview

Pit # 1 was backfilled with tailings to RL12m. Approximately 7500 vertical wick drains were then installed from a floating barge. The dewatered tailings surface was covered with geotextile, followed by a 2.5m thick preloading layer of waste rock over 70% of the surface area of the pit. A 0.5 to 1m thick cover of laterite was placed over the northern half of the pit to form a pond water interception layer. It does not appear that this laterite layer was incorporated into the 3D pit model produced by INTERA.

The next stage of backfilling and capping to be carried out over the next two years will involve placement of progressive lifts of waste rock (primarily type 1) to achieve a final above-grade domed landform. The backfill weight surcharge will cause entrained porewater to be expressed vertically upwards (PTF) through the vertical wicks, thus facilitating vertical consolidation of the tailings layer. As this consolidation occurs the tailings porewater will occupy pore space in the bottom horizon of deposited waste rock. The height to which this PTF layer reaches will be the critical determinant of solute egress from the capped pit

Solute Source Terms

There will effectively be three source term layers in Pit#1. The thickest layer will comprise deposited tailings with entrained pore (process) water. The next layer above this will be waste rock containing expressed pore water. This expressed water is called pit tailings flux (PTF) water in the INTERA 2014 reports. Overlying this PTF-saturated layer will be waste rock that is variably saturated as a result of seasonal downward percolation of infiltrating rainwater and lateral inflow of near-surface groundwater.

The three solute source terms of relevance for the (near surface) backfilled waste rock layer in Pit #1 will be:

- a downward component driven by leaching of solutes by infiltrating rainwater;
- a lateral component driven by inflowing near-surface groundwater and
- an upward component driven by PTF being expressed from the consolidated tailings.

These contributors to solute source strength are in relatively close proximity to the surface, with consequently the greatest potential for egress from the rehabilitated pit. As noted above in the commentary on source strength it is considered that solutes inputs have been underestimated over the short to intermediate term for the non-PTF saturated component of the backfilled rock and for the laterally inflowing groundwater.

The greatest sensitivity to solute egress over the short term is the extent to which the PTF lens rises into the waste rock backfill. The latest consolidation modelling indicates that almost all of the PTF will be expressed over the 6years following application of the backfill surcharge. Unless this PTF can be rapidly removed over a very short timeframe, the rate and extent of rise will be such that unacceptable egress of tailings-derived solutes will occur.

The analysis done by CSIRO (CSIRO 2104, p 116) indicates that the PTF level needs to be maintained below about +13m AHD to prevent this from occurring. However, the higher the PTF level rises into the backfill, even transiently, the greater the residual signature that will remain in the waste rock layer to be subsequently leached out. Thus active management of the PTF egress will be critical. This is the most critical issue in relation to the RL#0 tailings deposition issue since it is not the final level of the tailings per se that will determine the extent of solute egress, but rather both transient maximum and "final" (after extraction of PTF ceases) level of the PTF.

ERA proposes to actively manage the expressed PTF by withdrawing the water as it is expressed via two decant towers installed at the downgradient margin of the Pit. These towers will be extended vertically as the backfill is placed. Consolidation modelling indicates that 99% of the PTF will be expressed in the 6 years following the placement of backfill, with the majority of this occurring at the front end. This is a positive finding since it means that active management via withdrawal and treatment can be done while the brine concentrator is operating. However, given the rate at which the water will be expressed there is only a relatively narrow time margin to do this effectively, with very little room for "error". In particular, the brine concentrator will need to have high availability through this time.

The INTERA model assumes for its starting point that a certain amount of PTF has already been removed and that the lens of PTF water (ie the "pond" of PTF on top of the tailings interface) is at its near final position. The "problem" with this approach is that it doesn't capture the critical initial dynamics of PTF rise, in particular the maximum height that the PTF may reach in the backfill. Whilst it is understandable why the modelling was done this way, given the vagaries of operational variables during this period, it does raise the question of underestimating solute source strength that could occur as a result of transient wetting up of part of the backfill profile with PTF. This aspect is a significant weakness in the modelling. Hence I would recommend transient modelling to undertake a sensitivity analysis of the effect of rate of PTF withdrawal on potential maximum rise. This will be more complicated to do as it will be a "moving boundary" problem.

If the PTF level rises above +13m AHD then there is a high probability that minimally diluted tailings pore water will escape into Corridor Creek via shallow near-surface groundwater flow (CSIRO 2014). Recognising this sensitivity the CSIRO and INTERA modelling assessed what might happen if 75% (CSIRO), 90% (CSIRO, INTERA) and 95% (INTERA) of the PTF was to be removed. However, as noted above the starting point for these models was that these removals had already occurred, with no transient upwards wetting of backfill. The models did not explicitly address the issue of maximum transient rise of PTF into the backfill.

The key question from a practical management perspective is how much of the PTF TLF can actually be recovered via the decant towers. It might be "convenient" to consider that since 99% of the PTF is (theoretically) expressed over the first 6 years then all of it can be recovered. However, this is not realistic and so it is considered by this reviewer that inclusion of the 99% removal condition by ERA in its NOI is not viable. Indeed there is no discussion at all in ERA's NOI of what might be practically achievable. This is an important omission. In the absence of guidance to the contrary this reviewer suggests that 90% removal might be able to be achieved. Consequently further discussion about the model predictions will use 90% removal.

The modelling by CSIRO (CSIRO 2014, p116) indicates that with 90% PTF recovery the top of the PTF lens could be positioned below +4m AHD assuming that there is little or no vertical mixing between the PTF and recharge and groundwater inflow as these latter two components enter and fill the available backfill void space. In contrast the modelling done by INTERA predicts that this interface (ie top of the PTF) will be at +7m AHD. Both of these predicted levels are well below the "critical" level of +13m AHD determined by CSIRO.

Figure 2 below is copied from INTERA 2014a and shows the annual total load of Mg from the three major solute sources plotted as function of time to 10000y. The initial egress of Mg is dominated by the PTF source. This is predicted to largely decay away by 100y, with Mg load being dominated by leachate from the waste rock cap to 300y. After 300y the egress of solutes from the deeper tailings is predicted to make only a 40% contribution to the much reduced total annual loading of Mg over the remaining time of the simulation.

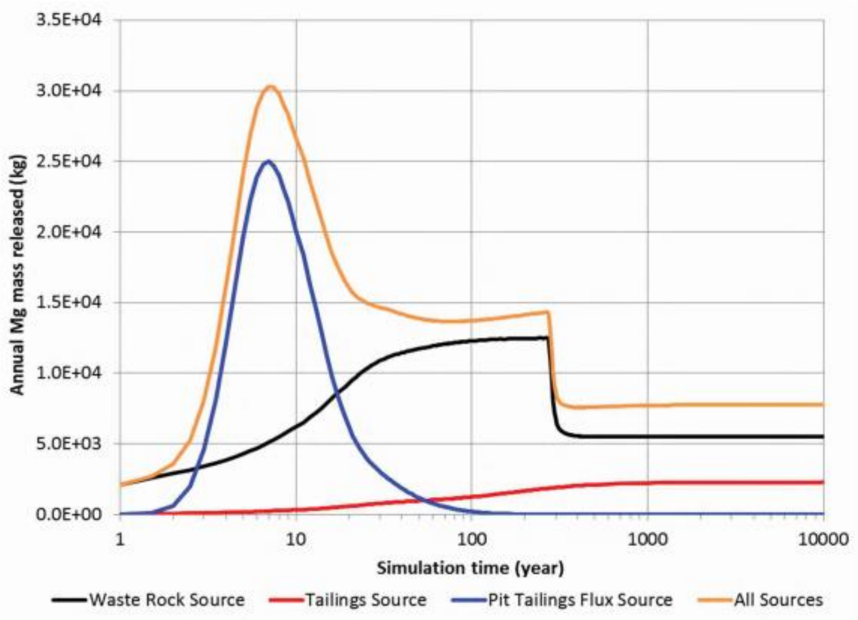


Figure 3.23: Comparison of Total Mg Loading From Waste Rock, Tailings, and Pit Tailings Flux (90% Removal) Sources

Figure 2: Mg Loadings from Pit #1 with 90% removal of PTF (from INTERA 2014a)

What is immediately apparent from Figure 2 is that there are three distinct time widows that need to be addressed by this assessment: 0-100y, 100-300y, and 300-10000y. For this reason it is **not appropriate** to present averages of the loads (and this applies to all of the COPC) over the whole period as indicators as overall performance, as this will be strongly weighted towards the greatly reduced solute loadings over the 300-10,000 period. The environmental impact of closure must be assessed on the peak solute egress and **not** on the average.

As noted above the toxicity of Mg depends on the Mg:Ca ratio in solution. Given that the initial solute egress will be dominated by the higher Mg:Ca PTF source term, then assessment of potential for environmental impact over the first 20y or so needs to account for this accentuating factor. After 20-50y the Mg:Ca ratio should return to one that is closer to the Mg/Ca ratio that is currently seen for leachate from waste rock.

The annual loadings of Mg presented in Figure 2 need to be placed into the context of potential environmental impact. Table 8 in ERA 2016 (Table 4 below) attempts to do this.

The problem with the compilation in Table 4 is that it only uses the long term average annual loadings for comparison with current RPA mean annual loads. This is inappropriate as noted above since such a comparison does not address the peak annual load for solute egress post closure, which is the most relevant environmental performance benchmark in the context of loads. The predicted peak total loading for Mg for 90% PTF removal is 30,000 kg/y (Table 6, ERA 2016), which is over 3 times higher than the annual average.

It should be noted that the data presented in Table 4 compare annual load predictions with the measured annual loads during the operational period. This is different to the issue of peak post closure concentrations which would need to be compared with the applicable water quality guideline values.

Table 4: Copy of Table 8 from ERA 2016 placing annual loads into context

Table 8: Mean annual operational loads for constituents of potential concern from the RPA compared to predicted annual loads from tailings and all Pit 1 sources (with 90% pit tailings flux removal) and the Annual Additional Load Limits

Constituents of potential concern	Units	Annual long term loads Pit 1 tailings	Annual long term loads all Pit 1 sources (90% pit tailings flux removal)	RPA mean annual loads: 2002 – 2013	Additional annual load limits
Magnesium	kg/yr	2,200	8,000	203,000*	N/A
Uranium	GBq/yr	0.015[a]	0.68	1.87**	88
Manganese	t/yr	0.980	1.1	0.064**	6
Radium-226	GBq/yr	0.01[b]	0.06	0.13**	13
Total ammonia nitrogen as N	kg/yr	300	310	ND	N/A
Nitrate	t/yr	2.5×10^{-4}	0.039	0.15**	4.4
Phosphate	t/yr	1.5×10^{-4}#	5.1×10^{-3}	0.008**	2.8
Polonium-210	GBq/y	0.015[c]	0.016	0.04**	7

Given that the current mean annual total load of Mg from the RPA is 203,000 kg/y then the predicted 30,000 kg/y peak load would appear to be quite small by comparison. Indeed it could be argued on this basis that since no detrimental impact has been detected in Magela Creek with current loadings from the RPA, then a loading which is almost 7-fold lower should be of no consequence. However, this comparison is only valid if the intrinsic toxicity of the two sources is the same. As discussed above this is not likely to be the case since the PTF which dominates the solute egress in the first 20y has a much higher Mg:Ca ratio than is currently the case for stockpile leachate and runoff. For Mg:Ca > 9:1 the chronic exposure Mg limit for 99% ecosystem protection reduces from 2.5 to 0.8 mg/L. Thus applying a scaling factor of 3 to the 30,000 kg/y prediction yields a number which is almost half the loading that is currently coming from the entire RPA. In this context it should be noted that this would be for the Pit# 1 source alone, not including exports of solutes from the rest of the RPA. That is not to say that the situation would be environmentally unacceptable. It is just that it would not be as apparently clear cut as per the argument that has been presented to date.

All of the analysis and conclusions that are subsequently presented in ERA's NOI are based on the unrealistic assumption that 99% of the PTF will be able to be removed by active management.

Another issue that may need to be addressed for Pit#1 is the possibility of efflorescences of MgSO4 developing at the downgradient end of the pit during the dry season, especially when the PTF load is at its peak. The following excerpt copied from INTERA 2014a indicates that the PTF-enriched plume reaches ground surface for a period of time.

"*The PTF source after 90% removal creates a shallow Mg groundwater plume that migrates out of Pit #1 with much higher concentrations than the Mg plumes from the waste rock backfill and tailings sources. The shallow PTF Mg groundwater plume reaches ground surface at the downgradient margin of Pit#1 by the second year, reaches Corridor Ck by 25 years and falls below 60 mg/L at the creek after 60 years.*"

It should also be noted from Figure 1 that whilst the PTF source decays away quite rapidly the total annual Mg loading from Pit #1 will be sustained at an elevated level for 300y or so by leachate from waste rock.

The modelling that has been done by INTERA proceeds on a yearly time step using annual loadings of Mg. INTERA (2014b) states that this was done because it would be too computationally demanding to run the model on say a monthly time step, incorporating seasonal variability, over the 10,000y period of the simulation. On the face of it this might appear to be a reasonable assertion. However, in practice this is not the case as the time window for impact of the major PTF source from Pit #1 is predicted to last for only a few decades. It is strongly recommended that the model be run on a monthly time step for say 40y to identify if there are likely to be any critical stress periods for solute egress during the annual seasonal cycle when PTF is the dominant source of COPC. This is an especially important issue to investigate because the annual pulse release of solutes from the pit is likely to be offset somewhat from the current situation where solute egress is dominated by within wet season seepage and runoff from above grade waste rock stockpiles.

COPC other than Mg

The use of Mg as a "tracer" to scale the concentrations/loads of the other COPC is a valid conservative approach. In practice there will be substantial attenuation of the other COPC by biogeochemical processes along the transport pathways. These processes, especially for U and Mn, have been extensively addressed previously by CSIRO (CSIRO 2014) and reiterated by INTERA.

However, there remain the issues raised above about (initial) source strength of groundwater and the extent of penetration of the PTF into the rock backfill. Each of these issues could increase the peak predicted Mg and consequently the predicted peak concentrations of COPC. In this context the same three time windows defined above should be used to predict concentrations of the COPC, noting the changes in primary source terms that occur through time. Currently most of the predictions that have been reported by INTERA and subsequently used by ERA for COPC other than Mg have been time averaged rather than peak values. Whilst use of peak values may not ultimately affect the assessed outcome it is not appropriate to use 10,000y time averaged values as the basis for assessing closure performance.

4.2 Pit #3

The closeout of Pit#3 will be very different to Pit#1, noting that Pit#3 is much closer to Magela Creek. An underfill platform (underdrainage system) of waste rock was constructed in the pit prior to the start of deposition of thickened tailings. Brine from treatment of process water will be injected at the base of this platform up to a maximum elevation of RL-118m. Tailings will be deposited between RL-100m and RL-20m. A cover of waste rock will then be placed over the tailings in a similar manner to that for Pit#1. Tailings from the U extraction circuit and from dredge reclaim of tailings from the tailings dam is currently being placed in the pit.

The biggest difference between Pit #1 and Pit#3 will be the absence of a significant PTF source. This is because the tailings will already be largely dewatered as a combined result of the underdrainage system and a higher initial wt% solids content of the deposited tailings.

The same comments that were made above for Pit#1 about the assumption of background concentrations of COPC for saturated waste rock and lateral groundwater sources apply to Pit#3. The additional source term that needs to be considered for Pit #3 is the process water treatment brine that is being injected at depth into the base of the waste rock platform. However, given the depth of this potential source and its high density it is expected to make very little contribution to the egress of solutes from the pit.

INTERA has modelled two scenarios, which include a low-permeability cap over the tailings, and a low-permeability cap at the top of the shallow waste rock backfill, to simulate the mitigation features of these caps on COPC transport. However there is some question on whether sufficient material is available on site for these caps to be constructed. If these caps can be constructed then the cap over the tailings would aim to minimise upward migration of tailings porewater over the longer term. The function of the cap over the surface of the waste rock will be to limit rainfall infiltration into the cap and hence reduce the flux of solutes from the waste rock over the very long term.

Figure 3 is copied from INTERA 2014b. This shows the contribution to total annual Mg load from all sources. Note that PTF is not a significant source of solutes for this pit.

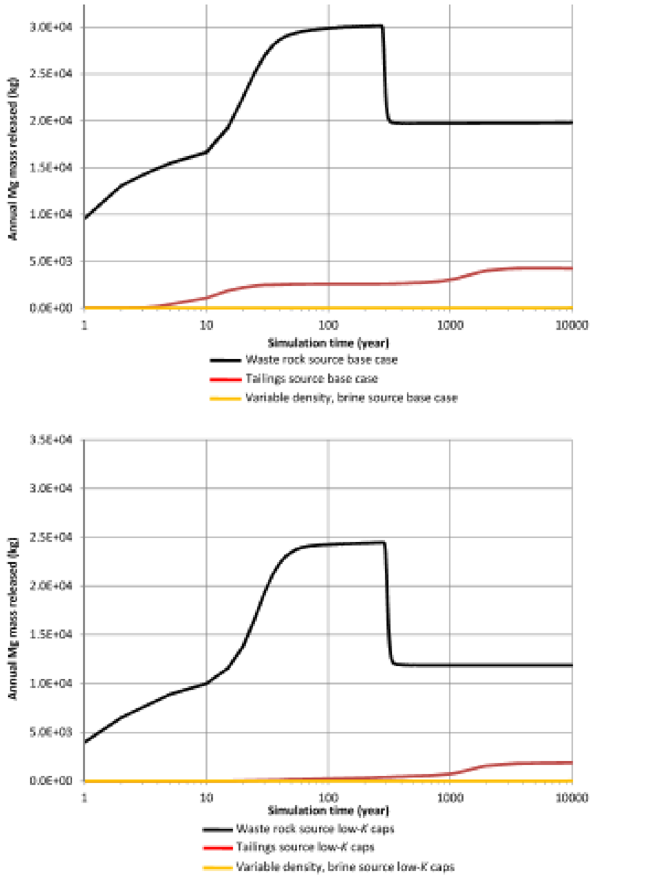


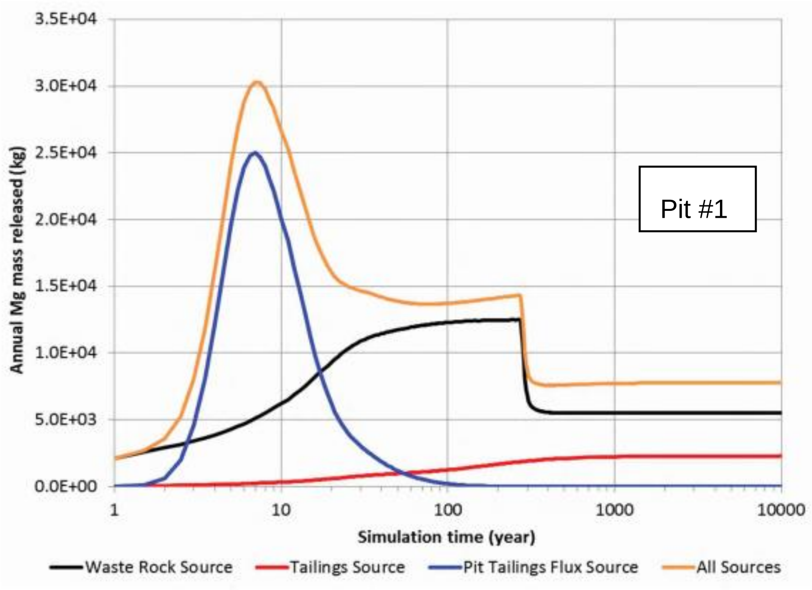
Figure 5.26: Total Mg Loading From Waste Rock, Tailings, and Brine to Magela Creek With and Without Low-Permeability Caps

Figure 3: Contribution to annual load of Mg from all sources – without caps (top) and with caps (bottom).

There are two panels in Figure 3. The uppermost panel is the “base case” with no additional amelioration. In the bottom panel the effect of incorporating low permeability layers above the tailings and on top of the waste rock backfill is shown. The annual load of Mg is dominated by leaching from the waste rock cap with the peak loading predicted to occur between years 20 and 200.

4.3 Pit #1 and Pit #3 Compared

The Mg time series plots for Pit #1 (top panel) and Pit #3 (bottom panel) are compared below in Figure 4. It can be seen that the predicted window of peak solute loading for Pit #3 is offset to a slightly longer (relatively speaking) time than Pit #1.



3: Comparison of Total Mg Loading From Waste Rock, Tailings, and Pit Tailings Flux (90% Removal) Sources

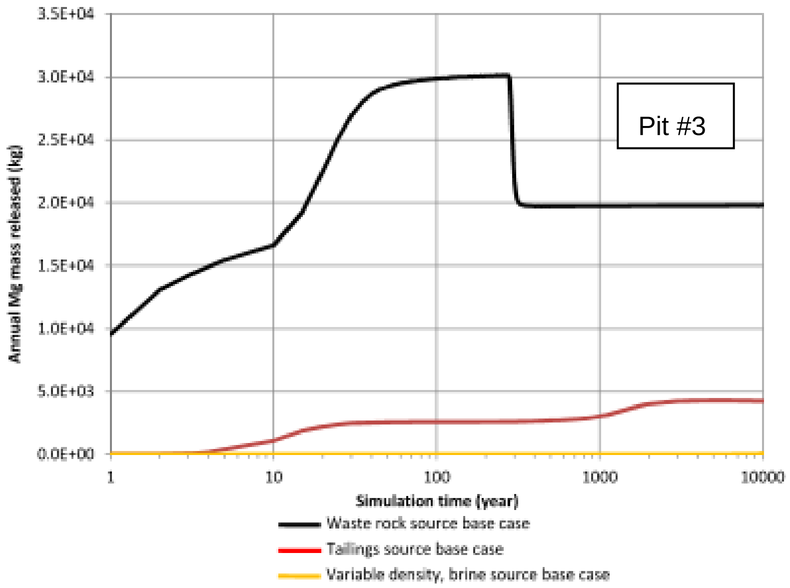


Figure 4: Comparison of time series annual Mg Loads for Pit#1 (INTERA 2014a; top) and Pit#3 (INTERA 2014b; bottom).

The most conservative scenario (ie no additional barrier layers) is shown for Pit #3 since the presence of these barriers does not make a great deal of difference to the peak loading (although there is predicted to be a substantial lowering of the long term loading).

Taken together (ie by simple addition of the total loads through time, assuming no interaction between Pit #1 and Pit #3) the time series plots in Figure 4 suggest that a peak loading of Mg of between 30 and 45 t/y will extend from about 7 to 300 years into the future, with a steep drop off after this time to a final plateau. This drop off is predicated on the assumption that the long term leachability of the waste rock will be equivalent to the current background manifested by country rock undisturbed by mining. Whilst this may be a reasonable limiting assumption the time at which the drop off will actually occur is very uncertain.

The other important point is that the first stage of this peak loading will be dominated by PTF from Pit#1 with its higher Mg:Ca ratio, while the second stage is predicted to be dominated by leachate from waste rock (lower Mg:Ca ratio). As discussed above, the potential environmental impacts of these two conditions will need to be specifically assessed taking into account the amelioration of Mg toxicity by Ca.

5. CONCLUSIONS

This review has focussed on the geochemical aspects of the modelling framework that has been implemented by INTERA, noting the comment on the hydrogeological aspects is the subject of a separate review.

- The selection of COPC is consistent with all of the prior work that has been done to identify those solutes most likely to be an issue at Ranger. Although it is not a COPC *per se* Ca needs to be included in the suite of solutes modelled by virtue of its strongly ameliorative effect on Mg toxicity. All COPC have been assumed to be conservative in the solute egress predictions made by INTERA. However, this may not be a valid assumption to use for Ca given its "protective" function. That is, if the concentration of Ca in the discharge is overestimated by virtue of assuming conservative transport, then an unrealistic prediction may be made of environmental significance in relation to the WQ guideline value that is used for Mg.
- The Mg source concentration assigned by INTERA for the vadose zone waste rock backfill is consistent with the existing empirical data set for Type 1 waters (the most relevant). In contrast, the source strength for this zone may have been substantially underestimated for U. .
- The use of a geochemical model coupling pyrite oxidation with dissolution of Mg (from chlorite) to predict the length of the time window for elution of above background concentrations of Mg from the waste rock vadose zone should be regarded as indicative only, given the numbers of assumptions that had to be made about initial pyrite content and oxygen concentrations in the backfill.
- It is documented in CSIRO (2014) that secondary minerals are forming within the tailings in Pit #1 as supersaturated phases precipitate. However this appears to be a kinetically slow process with no significant effect thus far in reducing the concentrations of COPC in tailings porewater. Hence it is reasonable to assume that the concentrations of COPC in tailings porewater (and in PTF) will be similar to those currently measured for a long time. There is no indication that concentrations of some COPC might increase through time in tailings porewater.
- The Mg ratio approach to estimating concentrations (and loadings) of COPC discharged from the site through time is appropriate, assuming conservative behaviour for them. However, the predictions may not necessarily be valid given the likely underestimation of some of the contributing source terms.
- The major sensitivity for solute egress from Pit #1 over 1st 50 years will be the amount of PTF that is initially extracted as the tailings consolidates over the first 6 years, including the time required for placement of backfill. Extracting the PTF as it is produced will be the key to ensuring that downstream environmental impact is minimised. It is inferred by ERA in its NOI for Pit #1 closure (ERA 2016) that 99% of the PTF will be removed. This reviewer disagrees with this proposition. In the absence of guidance to the contrary it has been assumed for this review that 90% removal is more realistic.
- The source terms for laterally inflowing groundwater have been underestimated, especially for the shorter term, given the likely presence of waste rock and tailings dam leachates in the up-gradient groundwater flow field. INTERA has assigned country rock (background) COPC values to this source in perpetuity.

- The initial COPC source strength of the saturated zone of waste rock has likely been under-estimated (substantially so for U) as it has been assigned “background” source strength in perpetuity. In practice this rock will contain a pre-existing elevated leachable load that will be eluted through time. This issue is likely to be of most import for Pit#3 given the greater thickness of this layer than for Pit#1. No distinction has been made between grade 2 waste rock and grade 1 waste rock in terms of leachable U, noting that grade 2 material will preferentially be placed at depth in the saturated zone of Pit#3. In this context CSIRO (2016) found a direct (linear) correlation between U content of the waste rock and concentration of U in leachate.

- The magnitude of the PTF-derived source in Pit#1 may have been significantly underestimated by virtue of a higher transient elevation of the PTF occurring in waste rock, compared with the model assumption that the final elevation corresponding to a given % removal is the starting point for the model. This is an issue since the PTF-wetted material will retain a significant proportion of the PTF solute load, despite subsequent drain down to the target removal level.

- The predicted peak load of 30,000 kg/y of Mg from the Pit#1 is substantially lower than the 203,000 kg/y on average (ERA 2016) that currently leaves the site. Hence it could appear that this load will not be an issue given that no detrimental downstream impact has been detected for the current annual loading of Mg. This conclusion would still be reached even if the predicted peak Mg loads have been underestimated by 50%. However, this 1st pass analysis does not take into account the higher Mg:Ca ratio in tailings-derived water and the fact that the current Mg ecotox guideline for chronic exposure is based on the much lower Mg:Ca ratio under the current operational condition. This aspect may require further consideration by SSB in its assessment of ERA’s NOI (ERA 2016) for the closure of Pit #1.

- Reference to Figure 4 shows that the combined effects through time of Pits 1 and 3 need to be considered. Simple addition of the predicted Mg loads from each pit through time provides a reasonable first pass basis for doing this. Running a combined Pits model would probably not provide much more insight. However, in this context it appears that the pre-existing (impacted) solute loads in groundwater in the areas between the domains defined by the pit footprints may not have been taken into account by the model. There will also be a substantial amount of waste rock remaining on the surface after the pits are backfilled. The contribution of this solute source to annual loads of Mg leaving the site may not have been adequately addressed by the model, and could be significant.

The issues identified above need to be addressed to ascertain whether they are likely to have a material effect on the model predictions by INTERA and the conclusions that have been based on them (see recommendations).

6. RECOMMENDATIONS

- Given the limited time available this reviewer has not been able to look in detail at the source strength assigned to waste rock for COPC other than Mg, U and Mn. It is recommended that a similar comparison as has been done in this review for Mg, Mn and U is done between the Type 1 and Type 2 datasets for the other COPC, noting that nitrate from blasting residues is more likely to be present in higher concentrations in Type 1 water.
- The effect on initial solute loads of not assuming background starting concentrations for COPC in saturated waste rock and in shallow groundwater should be quantified to determine if this is a significant omission in the predicted loads of COPC in the 50 years after pit backfill has been completed.
- The potential for a much higher Mg:Ca ratio in solute egress from Pit#1 over the initial decades post backfill should be assessed, noting that it may not be appropriate to assume conservative behaviour for Ca given its ameliorative effect on Mg toxicity.
- Transient modelling should be conducted to investigate the sensitivity of PTF rise in PIT #1 backfill to possible management scenarios (eg rate of removal lagging behind rate of production).
- For Pit #1 the model should be run on a monthly time step for say the first 40y to identify if there are likely to be any critical stress periods for solute egress during the annual seasonal cycle, when PTF is the dominant source of COPC. This is especially important because the annual pulse release of solutes from the pit is likely to be offset somewhat from the current situation where solute egress from the site is dominated by within wet season seepage and runoff from above grade waste rock stockpiles.
- Long term average values should not be used for comparative assessment over the whole 10000y time period as this strongly weights the result to the lower loads at longer times. The time window for peak loads should be used as the basis for post closure performance assessment since this will be the critical stress point for assessing the likelihood of success. In particular three time windows should be used for each pit, based on the time series predictions shown in Figure 4.
    - **For Pit #1:**
        - 0-50y for PTF efflux
        - 50-300 y for waste rock leachate
        - 300-10000 y for long term contribution
    - **For Pit #3:**
        - 0-10y for initial condition
        - 10-300 y for waste rock leachate
        - 300-10000 y for long term contribution
- The combined annual loading through time of Mg from Pits #1 and #3 plus the other potentially substantial contributions (eg surface waste rock and rehabilitated tailings dam footprint) to solute exports from the site need to be considered when comparisons are being made with current annual loads of Mg.

7. REFERENCES

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Esslemont (2015) Background Constituents of Potential Concern in Groundwater of the Ranger Project Area. 15 April 2015.

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INTERA (2014b) Final Report: solute egress mitigation modelling for ERA Ranger Pit 3 Closure. 1 July 2014.

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Appendix 7

Summary outcomes of the Groundwater Workshop hosted by the Supervising Scientist Branch, 5-7 September 2016

Ranger Groundwater Workshop

Jabiru Field Station

Monday 5 - 7 September 2016

Summary Record of Workshop

Attendees	**ATTACHMENT A**
Agenda	**ATTACHMENT B**
Acronyms	**ATTACHMENT C**

Summary of workshop:

The workshop engaged a broad range of stakeholders on the groundwater conditions within and surrounding the Ranger Uranium Mine in an effort to support Energy Resources of Australia Ltd (ERA) to progress the mine towards future rehabilitation and closure.

There was general agreement that the groundwater solute transport model prepared by INTERA, for ERA, is "fit for purpose" in that it provides conservative predictions of the timing and magnitude of peak solute loads to Magela Creek over a 10,000 year timeframe.

Ongoing monitoring within the Ranger project area, in the immediate term, will be important to improve calibration and to validate the groundwater models and the conceptualisations that underpin them. A number of groundwater focussed investigations and knowledge needs were identified by the stakeholders, which would support ERA in moving towards closure.

Day 1: Monday 5 September

Opening comments by Keith Tayler – SSB

Groundwater represents one of the most important contaminant pathways at Ranger. Groundwater conceptualisation and modelling are key (prediction) tools with which to assess contaminant transport to Magela Creek from the rehabilitated mine site.

The two overarching objectives of the workshop were to provide clear direction for ERA on any additional work that may be required to take the current groundwater modelling developed by ERA/INTERA to a level of acceptability, and what further groundwater associated work is required to be done. Therefore the focus of this workshop was groundwater.

Supervising Scientist Branch (SSB) is well equipped to evaluate the impacts of solutes to Magela Creek once concentrations are known, but confidence in the modelling and its ability to predict solute concentrations into the future is required.

Review work has been compartmentalised by SSB with consultants engaged to review the solute transport models, geochemistry and consolidation modelling provided by ERA to support closure related applications. ERA (through their consultant INTERA) provided the Ranger Conceptual Model (RCM) in early August 2016 to document the regional, site and 'area specific' hydrogeological conceptualisations. The RCM was also provided to/reviewed by the Department of Mines and Energy (DME), Geoscience Australia (GA) and the Office of Water Science (OWS). The review of the consolidation modelling was not discussed at the workshop due to time constraints.

Overview of Ranger Mine and ERA closure strategy – ERA

Presentation 1. ERA – Overview of Ranger and Closure

ERA provided an overview of the Ranger uranium mine over the past 35 years, and its closure strategy.

The Environmental Requirements for Ranger require that there be no change to the biodiversity of the surrounding environment, and that tailings are isolated from the surrounding environment for 10,000 years. To predict the role of groundwater as a potential pathway for tailings migration to the surrounding environment, ERA engaged their external consultant (INTERA) who have an extensive background in radioactive disposal modelling.

ERA provided an overview of a closure planning timetable for the 2012-26 period. It described various timeframes within which closure activities have been, or are expected to be, finalised. This included descriptions of the final landform evolution modelling.

Overview of Solute Transport Model(s) development (Pit 1 and 3) – INTERA

Presentation 2. INTERA – Part 1 – Ranger Conceptual Model *(numerical model development - pages 1-13)*

Since 2011 INTERA have been working with ERA to develop a numerical groundwater solute transport model to simulate solute movement from pit backfill materials (tailings and waste rock) to surface over a 10,000 year period.

An initial RCM was developed in 2012 using previous work developed by CSIRO, from which the Pit 1 and Pit 3 groundwater solute transport models were developed.

Key features of the Pit 1 and Pit 3 solute transport models include:

- Domain boundaries coincide with physical, geographical and geological features
- Calibration: 2005-06 period; incorporated 73 bores (42 adjacent to Magela creek)
- Deep bedrock layers (low hydraulic conductivity) were deactivated in the steady state model but were re-activated in the predictive model
- Peak loads predicted to be encountered within 270 years.

The group discussed relevant matters following the presentation. Topics of discussion included:

- Calibration of the model including factoring in seasons and use of two years of data.
- Using pump test data to show groundwater flow behaviour associated with faults.
- The model results for annual solute loadings post mining and how these compare to solute loads observed during mining.

Review of Solute Transport Model(s) (Pit 1 and 3) – DEWNR SA

Presentation 3. DEWNR - Model review

DEWNR presented a review on flow and solute transport models for Pit 1 and 3. The review was commissioned by SSB and managed by OWS.

The group discussed relevant matters following the presentation. Topics of discussion included:

- The groundwater model calibration dataset used and how climate variability was incorporated in the model.
- The temporal range of both the model (length of the run time in years) and the data used to calibrate the model (the period of time this data was collected over).

Review of geochemical aspects of closure modelling predictions – DR Jones Environmental Excellence

Presentation 4. DR Jones Environmental Excellence – Geochemistry review

Dr Jones from consulting firm Dr Jones Environmental Excellence, presented a review of the geochemical aspects of Pit 1 and Pit 3 closure modelling, which considered all factors affecting specification of COPC, estimation of source strengths, and assessment of loads. The review was commissioned by SSB and managed by OWS.

The group discussed relevant matters following the presentation. Topics of discussion included:

- Starting concentrations (source terms) of Contaminants of Potential Concern (COPC).
- Ratio of Magnesium to Calcium and consequences when the ratio increases above 9.
- The volume of expressed tailings water (Pore Tailings Flux - PTF) predicted to flow out of the tailings and through the base of Pit 1.
- The role of hydraulic conductivity in limiting the amount of PTF which can flow through the base and the pit wall and the percentage of PTF predicted to be removed through consolidation.

The absence of sulfate in the geochemical modelling was noted. Following this discussion, SSB requested a full summary of all ERA's available data on sulfate.

Conceptual Model Part 1: Chapters 1 and 2 – INTERA

Presentation 2. INTERA – Part 1 – Ranger Conceptual Model: Regional-scale model *(pages 13-27)*

INTERA presented the regional scale conceptual model. The regional scale conceptual model includes the greater region surrounding the Ranger Project Area as encompassed by the Magela Creek Watershed downstream of the mine to Mudginberri Billabong and upstream to flow meter MG0028.

The group discussed relevant matters following the presentation. Topics of discussion included:

- The use of the term 'aquifer', and problems with the term's use when considering groundwater flow and yield conditions over long time scales.
- Pre-mining surface water – groundwater connectivity conditions and the change in connectivity post-mining.
- Groundwater model parameterisation.
- Groundwater pathways, flow directions and variations to these attributes as a function of the geology and depth.

Conceptual Model Part 2: Chapters 3 and 4 – INTERA

Presentation 5. INTERA – Part 2 – Site-wide scale model

INTERA presented the site-wide scale conceptual model. The site wide conceptual model includes the region bounded by Mudginberri Billabong in the north, the Ranger Fault in the south, Gulungul Creek in the west and and Georgetown Creek in the east.

The group discussed relevant matters following the presentation. Topics of discussion included:

- Groundwater conditions in the "Mine Bore-L (MBL) Zone" to the south and south west of Pit 1 and how this zone of higher hydraulic conductivity was incorporated into the groundwater model.
- Groundwater recharge conditions in the Ranger 3 Deeps water producing zone.
- Surface water – groundwater connectivity. Specifically; discharge areas, discharge quantity, chemistry data and potential changes to these conditions post-mining.

Conceptual Model Part 3: Sections 5.2 and 5.3 – INTERA

Presentation 6. INTERA – Part 3 – Areas of interest and concern

INTERA presented the areas of interest scale (Pits 1 and 3 and all waste rock) models. These models are stand alone and individually incorporate Pit 1, Pit 3 and the proposed rehabilitated landform respectively.

The group discussed relevant matters following the presentation. Topics of discussion included:

- Potential sources of contaminants of potential concern (COPC) within the final landform.
- The risks posed by key COPCs (Magnesium, Uranium) to organisms.
- The relationship between the conceptualisations for Pits 1 and 3 and waste rock and other areas of concern presented by INTERA (see below).
- Groundwater and conceptual model uncertainty.

Conceptual Model Part 4: Sections 5.4 to 5.7 – INTERA

Presentation 7. INTERA – Part 4 – Tailings storage facility (TSF)
Presentation 8. INTERA – Part 4 – PAA
Presentation 9. INTERA – Part 4 – LAA
Presentation 10. INTERA – Part 4 – R3D

INTERA presented the following areas of interest/concern models: TSF, PPA, LAA and R3D. Due to time constraints, there was no discussion or questions following these presentations.

Conceptual Model Part 6: Section 5.9 – INTERA

Presentation 11. INTERA – Part 5 – Screening

INTERA presented a qualitative ranking (screening) of areas of interest/concern post closure divided by soil, groundwater and surface water.

The group discussed relevant matters following the presentation. Topics of discussion included:

- Groundwater flow and chemistry conditions in the vicinity of the TSF, including driving groundwater head from the TSF and the effect of the sealed TSF floor on groundwater flow.
- Preferential flow paths (e.g. faults or fracture networks) and the impact of these on groundwater quality and flow.

Ranger Project Area: Geology and geophysics – ERA

Presentation given by ERA, but copy not provided.

ERA provided an informative overview of the geology and geophysics of the Ranger Project Area.

The group discussed relevant matters following the presentation. Topics of discussion included:

- The capacity of faults to transmit groundwater.
- The height of tailings deposition in Pit 3 and Pit 1.
- The geomorphology of the Magela Creek channel, including how the channel supports biodiversity within Magela Creek.

Workshop Wrap-Up and Next Steps – SSB

The key issues were discussed – open forum. A summary of high-level, non-technical issues to assist in moving the process towards closure and rehabilitation was the focus. To support this outcome, a number of potential next steps were identified. These included:

- Understanding and predicting finer temporal (weekly/monthly/seasonal) details and quantities of solute transport to surface waters both immediately post decommissioning and up to peak loading.
- Validation and, eventually, re-calibration of groundwater flow and solute transport models through ongoing monitoring and gathering of new data.
- Improve understanding and clarification of COPC source terms.
- Reactive transport analysis of calcium.
- Investigate potential contaminant plume below the TSF.
- Undertake focussed studies on specific areas, including the TSF, Djalkmara Sands, Magela Creek, the “MBL higher permeability zone” and faulting in Pit 3 walls.
- Analysis of final landform design to prevent gully erosion exposing tailings, and address risks associated with break of slope erosion.

A surface water and TSF plume model were noted to be in development.

INTERA were commended on the enormous amount of work they had undertaken to date and for their significant participation during the workshop.

Other presenters and participants were thanked for their substantial contributions.

Meeting closed 11:10 am Wednesday 7 September.

Ranger Groundwater Workshop (5-7 September 2016) – Attendee List

Attendee	Organisation	Expertise/Position	Attended tour of Ranger site
Tim Eckersley	ERA	General Manager Operations	
Sharon Paulka	ERA	Manager Water and Closure	Y
Andrew McLellan	ERA	Senior Geophysicist	Y
Michelle Iles	ERA	Principal Advisor Environmental Studies	Y
Stephanie Miller	ERA	Manager Health, Safety, Environment, Communities and Water	
Sarah Reid	ERA	Water Management Specialist	Y
Ben McTavish	ERA	Superintendent Water and Closure	Y
John Sigda	INTERA	Principal Hydrogeologist	Y
John Pickens	INTERA	Principal Hydrogeologist	Y
Chris Malcolm	Mirarr – GAC	Business Improvement Manager, GAC	
Ian Hollingsworth	Mirarr - GAC	Consultant	
Adam Thompson	NLC	Representative of Northern Land Council	
Peter Waggitt	DME	Director, Mining Compliance	Y
Gavin Otto	DME	Senior Mining Officer	Y
Keith Tayler	SSB	A/g Assistant Secretary	Y
Kate Turner	SSB	A/g Director, Supervision and Monitoring	Y
Ty Felmingham	SSB	Hydrogeologist	
Adrian Costar	SSB	Senior Hydrogeologist	Y
Rick Van Dam	SSB	Director, Environmental Research Institute of the Supervising Scientist	
Sean Fagan	SSB	Manager, Jabiru Field Station	
Andrew Harford	SSB	Ecotoxicology (Program Leader)	
Chris Humphrey	SSB	Aquatic Ecosystems Protection (Program Leader)	
John Lowry	SSB	Landform Modeller	
Mike Saynor (Mouse)	SSB	Geomorphologist	
Lisa Chandler	SSB	Aquatic Ecologist	
Berlinda Bowler	SSB	Senior Policy Officer	
Peter Baker	SSB	Principal Geoscientist	Y
Mitchell Bouma	OWS	Geologist	Y
Carl Zimmermann	OWS	Hydrogeologist	Y
Moya Tomlinson	OWS	Groundwater ecologist	
Lucy Lytton	GA	Senior Hydrogeologist	Y
Sarah Marshall	GA	Hydrogeologist	Y
Chris Harris Pascal	GA	Hydrogeochemist	Y
Jessica Northey	GA	Hydrogeologist	Y
Juliette Woods	DEWNR	Principal Groundwater Modeller	Y
Lloyd Sampson	DEWNR	Principal Hydrogeologist	Y
Daniel Wohling	DEWNR	Senior Hydrogeologist	Y
David Jones	Consultant	Environmental Geochemist, D R Jones Environmental Excellence	Y

Ranger Groundwater Workshop Agenda

Monday 5 September		
1000	Site Tour	Participants to meet at SSB Jabiru Field Station (JFS) for a 10am departure.
1200	Lunch	Travel back to JFS for lunch
1300	Opening comments	Keith Tayler (SSB)
1330	Overview of closure strategy	ERA
1400	Overview of Solute Transport Model(s) development • Pit 1 • Pit 3	INTERA to present
1430	Solute Transport Model reviews (30-45 mins): • Pit 1 • Pit 3	SSB consultant to present followed by general discussion on topic
1600	Break	
1630	Geochemistry review (30-45 mins): • Site-wide	SSB consultant to present followed by general discussion on topic
1800	Conceptual Model Part 1: Chapters 1 & 2: • Background; objectives; development of CM	INTERA to present followed by general discussion on topic
1830	Close for day	
Tuesday 6 September		
0800	Conceptual Model Part 2: Chapters 3 & 4: • Regional CM • Site-wide Scale CM	INTERA to present followed by general discussion on topic This includes geology along with features and processes on a regional and site-wide scale
1030	Break	
1100	Conceptual Model Part 3: Sections 5.2 & 5.3: • Pit 3 CM • Pit 1 CM	INTERA to present followed by general discussion on topic
1300	Lunch	
1330	Conceptual Model Part 4: Sections 5.4, 5.5, 5.6 & 5.7: • TSF CM • Processing Plant Area CM • LAA CM • R3 Deeps CM	INTERA to present followed by general discussion on topic
1600	Break	
1630	Conceptual Model Part 5: Section 5.8 (plus low-K cap assessment): • Landform Waste Rock CM	INTERA to present followed by general discussion on topic
1730	Close for day	
Wednesday 7 September		
0800	Conceptual Model Part 6: Section 5.9: • Screening evaluation of areas of concern/interest	INTERA to present followed by general discussion on topic
0900	Conceptual Model – ERA's Perspective	ERA
0930	Closing comments	Keith Tayler (SSB) & general discussion
1100	Closure (morning tea)	

Acronym	Definition
BPT	Best practicable technology
Ca	Calcium
COPC	Contaminants/constituents of potential concern
DEWNR	Department of Environment, Water and Natural Resources, South Australia
DJ	David Jones, D R Jones Environmental Excellence
DME	Department of Mines and Energy
ERA	Energy Resources of Australia Limited
ET	Evapotranspiration
GAC	Gundjeihmi Aboriginal Corporation
GA	Geoscience Australia
INTERA	INTERA Geoscience and Engineering Solutions
ITWC PFS	Integrated Tailings, Water and Closure Pre-feasibility Study
LAA	Land Application Area
MBL	Mine Bore L - MBL is a zone (based on the MB-L bore) of relatively higher permeability in the south-east part of Pit 1
Mg	Magnesium
Mn	Manganese
NLC	Northern Land Council
OWS	Office of Water Science Branch, Department of the Environment and Energy
PPA	Processing Plant Area
PEST	Model-Independent Parameter Estimation and Uncertainty Analysis
PTF	Pit tailings flux (expressed tailings water)
R3D	Ranger 3 Deeps
RCM	Ranger Conceptual model
RL	Reduced level
SSB	Supervising Scientist Branch, Department of the Environment and Energy
TAN	Total ammonia N
TSF	Tailings Storage Facility
U	Uranium