Decision Report

Application for Works Approval

Part V Division 3 of the *Environmental Protection Act 1986*

Works Approval Number	W6641/2022/1
Applicant	Iluka Resources Limited
ACN	008 675 018
File number	DER2022/000035
Premises	Eneabba Mineral Sands Mine Mining Lease M267SA ENEABBA W6518 As defined by the premises maps attached to the issued works approval
Date of report	14 June 2022
Proposed Decision	Works approval granted

Paul Newell
Senior Manager, Process Industries
an officer delegated under section 20 of the *Environmental Protection Act 1986* (WA)

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1. Decision summary

This decision report documents the assessment of potential risks to the environment and public health from emissions and discharges during the construction and operation of the premises. As a result of this assessment, works approval W6641/2022/1 has been granted.

2. Scope of assessment

2.1 Regulatory framework

In completing the assessment documented in this decision report, the Department of Water and Environmental Regulation (the department; DWER) has considered and given due regard to its regulatory framework and relevant policy documents which are available at https://dwer.wa.gov.au/regulatory-documents.

2.2 Application summary and overview of premises

On 20 January 2022, the applicant submitted an application for a works approval to the department under section 54 of the *Environmental Protection Act 1986* (EP Act).

The application is to undertake construction works relating to the construction of the Eneabba Rare Earth Refinery (ERER) and the Yellow Dam North tailings storage facility at the premises. The premises is approximately 8 km south of the Eneabba township. The ERER will have an operational life in excess of 20 years and the operating schedule for ERER is 24 hours per day, 7 days per week, continuous flow throughput.

The premises relates to the category 44 and assessed production / design capacity under Schedule 1 of the *Environmental Protection Regulations 1987* (EP Regulations) which are defined in works approval W6641/2022/1. The infrastructure and equipment relating to the premises category and any associated activities which the department has considered in line with *Guideline: Risk Assessments* (DWER 2020) are outlined in works approval W6641/2022/1.

The general site layout for the ERER and Yellow Dam TSF is shown in Figure 1.

2.2.1 Eneabba Rare Earth Refinery (ERER)

Open pit mining at Eneabba started in the 1970s under the *Mineral Sands (Eneabba) Agreement Act 1975*. Mining covered an area of around 1,500 ha and operations at the site were idled in 2013.

Mineral sands processing has occurred at Iluka's Narngulu Mineral Separation Plant (MSP) since 1975. By-product from processing at Narngulu MSP is currently transported 150 km by road to Eneabba. The MSP by-product have been on average 30,000 tonnes per year and are dependent on Narngulu MSP production volumes and the mineral composition of the Heavy Mineral Concentrate (HMC) feed sources. The MSP by-product, comprised of about 20% monazite, has been stored in the Eneabba Monazite Pit (EMP) since 1994. The 1994 Radiological Council of WA (RCWA) and Department of Mines, Industry Regulation and Safety (DMIRS) approval to store the MSP by-product in the EMP, was obtained after the market for the product was no longer viable. The approval was conditional that Iluka would pursue the secondary processing and sale of the stored by-product in the future.

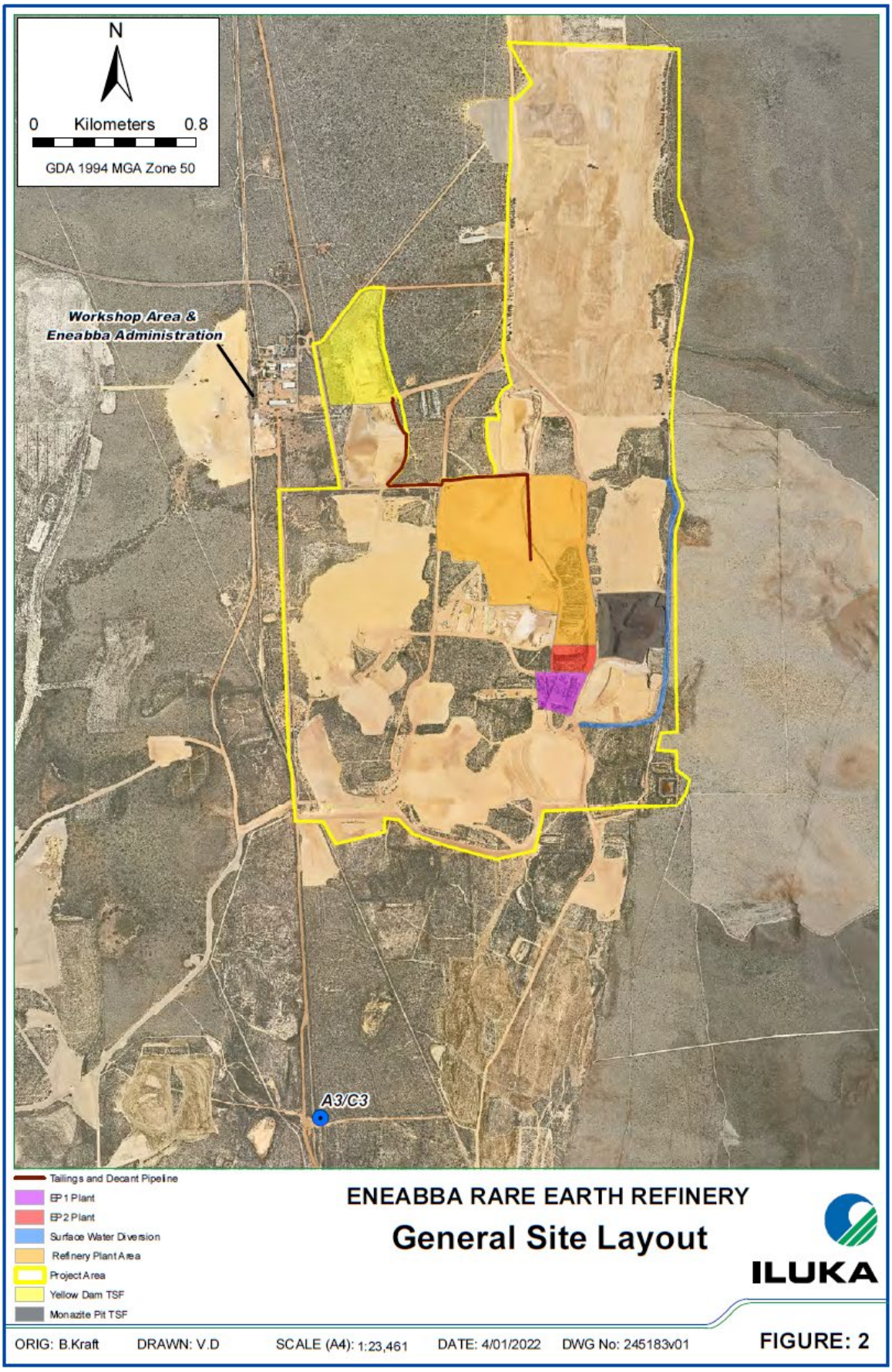


Figure 1: Eneabba rare earth refinery – general site layout.

The ERER plant is expected to have a rare earth concentrate feed rate of up to approximately 65,000 tonnes per annum (tpa) to produce up to 25,000 tpa of contained rare earth as oxides or carbonates based upon market specifications. The final rare earth products will comprise purified nonradioactive dysprosium (Dy) oxide, terbium (Tb) oxide, samarium-europium-gadolinium (SEG) carbonate, Heavy Rare Earth Elements and Yttrium (HREY) carbonate, praseodymium (Pr) oxide, neodymium (Nd) oxide, neodymium-praseodymium (NdPr) oxide, lanthanum (La) oxide and cerium (Ce) carbonate. Yttrium may be recovered as a separate oxide product in the future through adjusted operational settings and equipment configuration. A by-product will be ammonium nitrate solution.

The key infrastructure required for the ERER is depicted in Figure 2 and includes:

- Rare Earth Refinery:
  - Feedstock preparation
  - Roasting and leaching
  - Off-Gas Treatment
  - Purification
  - Separation
  - Product Finishing
- Solid Waste Disposal and Storage (Yellow Dam North TSF)
- Liquid Waste Management infrastructure
- Water Management infrastructure
- Supporting Infrastructure
- Reagents storage and transfer infrastructure

Feed Preparation

Refinery feed will comprise the rare earth concentrate material from the Eneabba Phase 2 (EP2) plant, which will be piped in via slurry. The rare earth concentrate material is mixed with sulfuric acid and transferred into the kiln for roasting.

The applicant also proposes to accept future feed stocks from other Iluka operations and non-Iluka rare earth concentrate sources (refer to section 3.1.1). Non-Eneabba material will be fed to the plant through rotating/tipping containers into a hooded and vented hopper that feeds directly into the acid mixing tank (refer to ‘Concentrate Feed System’ in Figure 2).

Roasting and Leaching

The combined sulfuric acid and rare earth concentrate will be heated in the kiln to a temperature that will form soluble rare earth sulfates. The resulting solids from the kiln is mixed with water to form a slurry containing dissolved rare earth sulfates.

Off Gas Treatment

The roasting kiln off gas treatment system will consist of a venturi scrubber system, spray tower, wet electrostatic precipitator, mist eliminator and acid recovery tanks, with cleaned off gas discharge via a stack. The off gas treatment system will include apparatus to recover the sulfurous gas emissions and acid vapour back into process and ensure the exhaust gas emissions meet the emissions concentrations included in Table 3 of this Decision Report (replicated from the Eneabba Mineral Sands Phase 3 Air Quality Assessment (ETA 2021)).

Other dust points will have either bag filters or wet scrubbers installed to manage fugitive emissions.

Purification

Impurities are precipitated and removed from the solution by neutralisation with magnesia and precipitation of iron phosphate with ferric sulfate. The precipitate is the main solid waste stream, consisting of sulfates (mainly calcium), phosphates (mainly iron) and oxides/hydroxides of impurities.

Product Finishing

Separated rare earth element products are precipitated from each stream using ammonium bicarbonate, and in the case of the high value products, the carbonate products are heated and converted into oxides.

The ERER process flow diagram for the ERER is represented in Stage 3 of Figure 2.

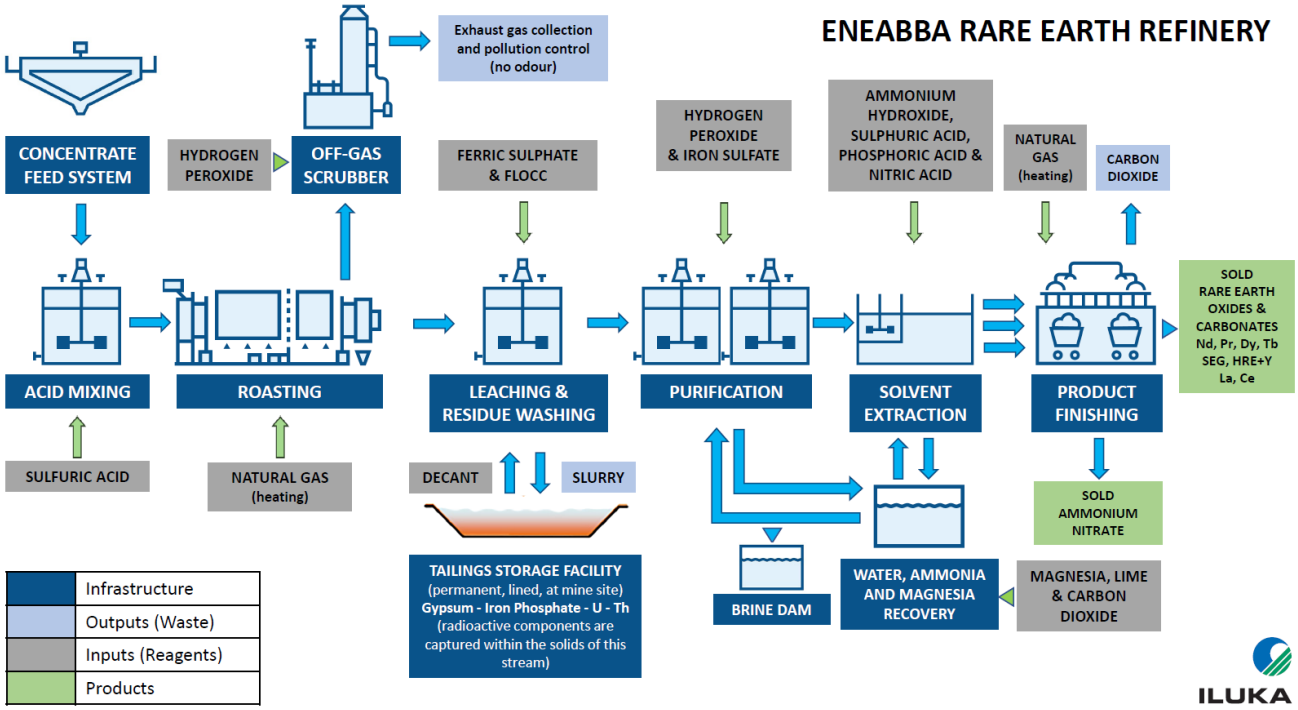


Figure 2: ERER Process flow diagram – Stage 3

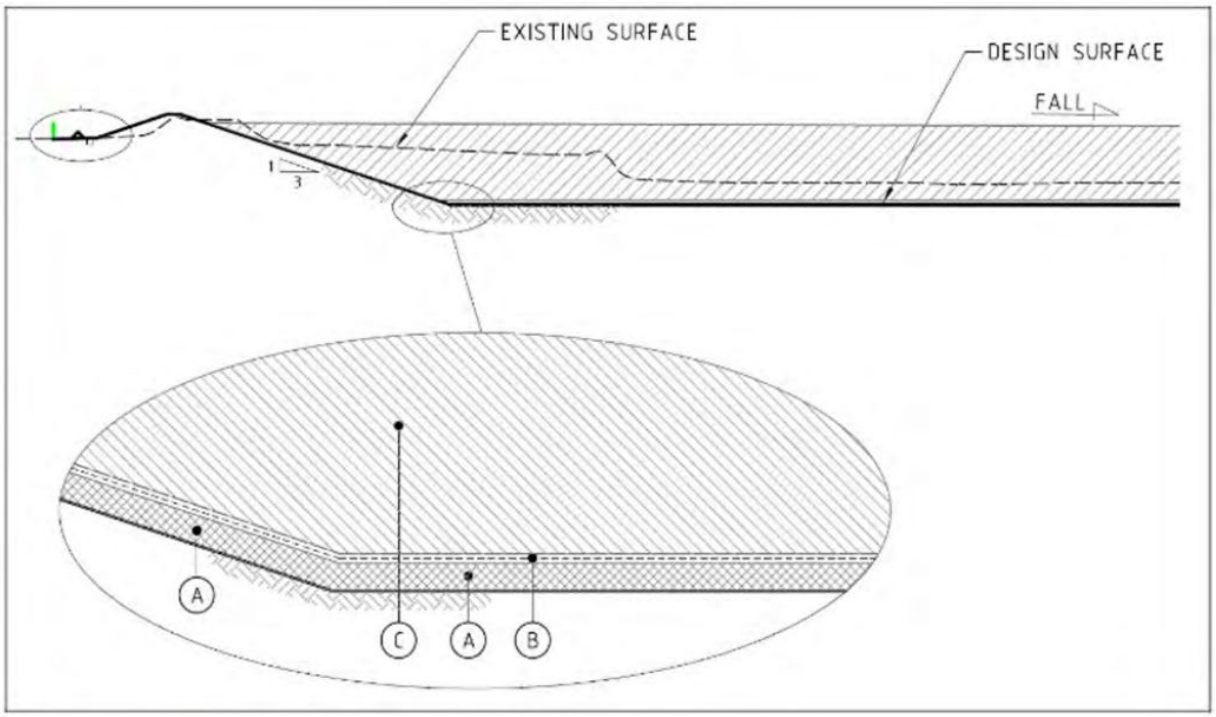
2.2.2 Yellow Dam North Tailings Storage Facility (TSF)

Solid waste from the ERER will be combined, collected and disposed of, as tailings into a purpose-built Yellow Dam North TSF where the excess water from the surface will be decanted and returned for processing.

To achieve safe storage the TSF was designed to be contained below ground (no flow failure) and the base be cut to a maximum depth of 2m above the groundwater level (average depth of 20 m).

A leakage detection and collection system will be installed at the southwestern corner, at the basin of the pit. The leakage detection system will be used to detect any leakage or rupture within the liner/s. A collection sump will be located at the basin of the pit to remove primary liner leakage and reduce pressure on the secondary liner.

A water monitoring sensor can be lowered into the HDPE riser pipe to the bottom of the collection sump to determine if there is any leakage water. Regular readings will be taken throughout the operational life and beyond. If water is found in the leakage detection system, it will be removed as soon as possible to avoid the risk of water head forming on the second HDPE liner.



A description of the layer works depicted above follows:

- A. Clay (Low Permeability) Foundation
- B. Synthetic Liner System (including HDPE)
- C. Tailings Deposit.

Figure 3: Yellow Dam TSF liner system

The Yellow Dam North TSF will be approximately 550m x 300m have a capacity of approximately 1,300,000 tonnes of tailings with a life of 5.4 years based on a conservative estimate of waste production volumes. Storage capacity is dependent on the volume of supernatant water extracted from the TSF during operation which is in part, dependent on the following variables:

- tailings settlement rates;
- evaporation and rainfall; and
- slurry water and ERER water requirements.

Tailings deposition rates are affected by the particle size distribution of the tailings waste and the ability for the applicant to manage deposition rates and locations to control the pond size and location for extraction via decant via floating turret. Figure 4 depicts the water balance for the Yellow Dam TSF, identifying that the ERER has greater water requirements than what can be abstracted through decant. However, based on particle size and settled density (refer to 3.1.2), settling times may be long and may restrict increases to the projected abstraction rates via the floating decant infrastructure. The applicant has committed to conducting further settling rate testing, which will assist in determining viable abstraction rates from the Yellow Dam TSF.

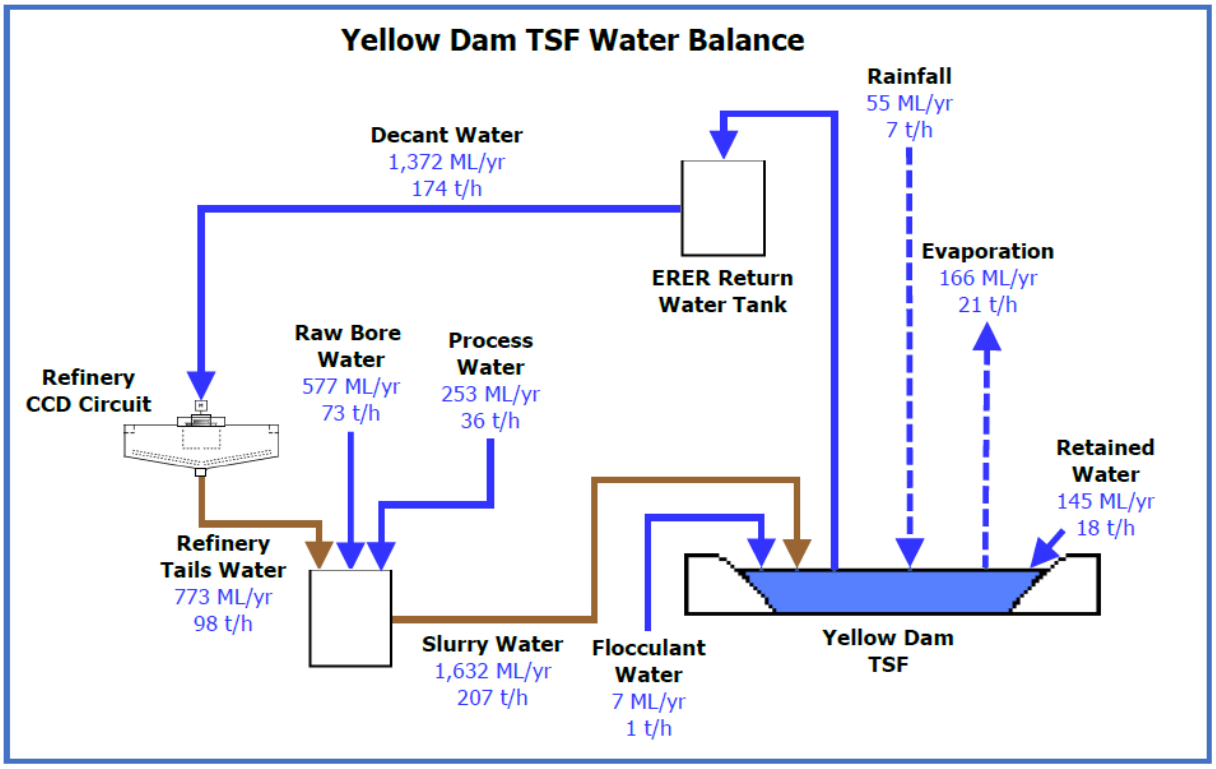


Figure 4: Water balance for the Yellow Dam TSF

Pipelines will be constructed within existing disturbed areas to transfer tailings and return water to and from the plant. The tailings transfer pipelines will be located within earthen bunds to minimize the extent of any potential leaks. No intermediate storage ponds are required.

2.2.3 Reagent, hydrocarbon and hazardous waste storage

The applicant proposes different containment systems (Table 1) for the various hazardous product inputs (reagents), fuels and wastes. Each containment system has consideration given to the types of chemicals stored, volumes required and the standards required for safe storage and handling.

The reagents required for the processing of the rare earth concentrate are detailed in Table 2. Large volumes of reagents/reagents with quantities over 100 tonnes will be stored within purpose built bunded tanks in accordance with Australian Standard (AS) 1940, AS 3833 or AS 3780 and the *Dangerous Goods Safety Act 2004* (WA). Reagents with quantities less than 100 tonnes will be stored in bulk boxes/bags within hardstand bunded areas in accordance with AS 1940, AS 3833 or AS 3780 and the Dangerous Goods Safety Act, 2004 (WA).

Table 1: Containment specifications

Containment reference	Material stored	Containment specifications
Yellow Dam TSF	Tailings (refer to section 2.2.2 and Figure 3) Total capacity of capacity of approximately 1,300,000 m^3	Lined with low permeability compacted clay layer (or equivalent) which is used as an HDPE liner foundation and provides an additional low permeability barrier should the geosynthetic liner system leak (Figure 3). This layer is installed after the basin area and pit slope batters are cleared and smoothly rolled. Where a local clay source is not identified a geosynthetic clay liner will be utilised. The base of the TSF will be scarified and rolled in

		accordance with the liner manufacturers preparation requirements. A geosynthetic liner system (HDPE 1.5 mm (Primary layer), geofabric (protection layer, BIDIM A24[1] or similar), Flownet leakage detection/ collection layer, geofabric (protection layer) and HDPE 1.5 mm (secondary layer). Diversion drains and bunds will be installed around the TSF to prevent access of stormwater. Refer to section 2.2.4.
Tailings and return water pipelines	Tailings and recovered water from the TSF	Placed in earthen bunds and equipped with automatic cut-outs in the event of a pipe failure. Pipelines to be inspected daily during operation.
Feed slurry pipelines	Ore concentrate from EP2	The ore concentrate from EP2 will be placed in a larger diameter HDPE pipe, incorporating leak detection and buried underground.
Brine Bleed Evaporation Pond	Brine from the RO Plant	Minimum 1.0mm thick HDPE liner. Pond will have adequate capacity to ensure a 1:100 rainfall event can be contained and will maintain a minimum freeboard of 500mm.
Sulfate Waste Dam	Spent sulfate waste from magnesia recovery system. Spent sulfate volume up to 10,000 m^3.	Minimum 1.0mm thick HDPE liner Pond will have adequate capacity to ensure a 1:100 rainfall event can be contained and will maintain the minimum 500mm freeboard.
Stormwater Dam (2)	Two stormwater dams containing at least 13,000 m^3 of rainwater runoff from the ERER.	Minimum 1.0mm thick HDPE liner. Ponds will have adequate capacity to ensure a 1:100 rainfall event can be contained and will maintain a minimum freeboard of 500mm
Reagents and hydrocarbon storage	Total storage of up to 4,100 tonnes of reagents (refer to Table 2)	Storage in accordance with Australian Standard AS3833. Bunding of bulk reagent storage area Collection sumps in the event of a spillage, pumped back into storage tank
Hydrocarbon storage	Up to 110,000 L of diesel fuel	One 110,000 L self-bunded, horizontal above-ground tank situated on an earthen pad. Designed and manufactured to Australian Standards AS1692 and constructed/handled in accordance with AS1940.

Note 1: Refers to a non-woven geotextile layer with strength in both directions and used for protecting critical liners.

Table 2: Approximate reagent storage requirements

Reagents	Concentration	Form	Quantity stored (tonnes)
Sulfuric acid	98.5%	Liquid	860
Quicklime	>80% Available CaO	Solid	850
Ferric sulfate	>60% as a liquid; or >95% as a solid	Liquid or solid	260
Magnesia (MgO)	>90%	Solid	45
Nitric acid (HNO_3)	62-68%	Liquid	1,000
Anhydrous Ammonia liquid (NH_3)	100%	Liquid	130
Phosphoric Acid (H_3PO_4)	85%	Liquid	15
Carbon Dioxide (CO_2)	99.5%	Liquid	150
Hydrogen peroxide	70%	Liquid	60
Kerosene (DeAromatised)	100%	Liquid	8
Solvesso 150 (Octanol)	100%	Liquid	1
TBP (Tributyl Phosphate)	99%	Liquid	1
PC88A (2-ethylexylphosphonic acid mono-2ethlhexyl ester)	99%	Liquid	1
Aliquat 336 (Quaternary ammonium salt)	100%	Liquid	1
Ammonium Nitrate Byproduct	60%	Liquid	720
Flocculation agents	N/A	Liquid	10
Water Treatment and Refinery Additives	N/A	Liquid	20
Refinery Additives	N/A	Solid	20

Reverse Osmosis (RO) brine pond

The process is designed for zero liquid discharge. Ammonia and magnesia is recovered and re-used in the process, and water is purified using microfiltration and reverse osmosis, producing a small quantity of sodium rich brine (<2tph), which is captured in the HDPE-lined Brine Bleed Evaporation Pond. The 2ha Brine Bleed Evaporation Pond will have a capacity of approximately 10,000m^3.

Capacity of the Brine Bleed Pond will be maintained by removing the magnesium sulfate evaporite from the pond for use in offsite agricultural purposes (Iluka, 2021).

2.2.4 Surface water management

Surface water management infrastructure will be constructed to divert water away from the ERER Plant to collection sumps. This will prevent flooding and capture potentially contaminated water that falls within operational areas. The infrastructure will include drains, diversions and stormwater collection ponds and will be constructed in accordance with relevant guidelines to ensure effective management of flows.

A 1km-long drain will be installed to the east of the ERER facility to convey runoff to the south and into the South Depression. A Surface Water Modelling and Impact Assessment (Water

Technology, 2021) identified that to prevent ingress of surface water from beyond the proposal area, the drain should meet the following minimum dimensions:

- Bottom width – 1.0 m
- Top width 5.0 m
- Depth – 0.5 m
- Batters – 1V:4H

To prevent uncontaminated stormwater entering the Yellow Dam TSF, an earthen bund wall will be constructed to keep surface water away from the toe of the TSF in the event of a >1% Annual Exceedance Probability (AEP) flood level. It is expected that this type of rainfall event will result in Probable Maximum Flood levels to the eastern side (upstream) of the TSF to reach up to 3.3m. Figure 5 depicts the anticipated location of surface water pooling during a >1% AEP rainfall event.

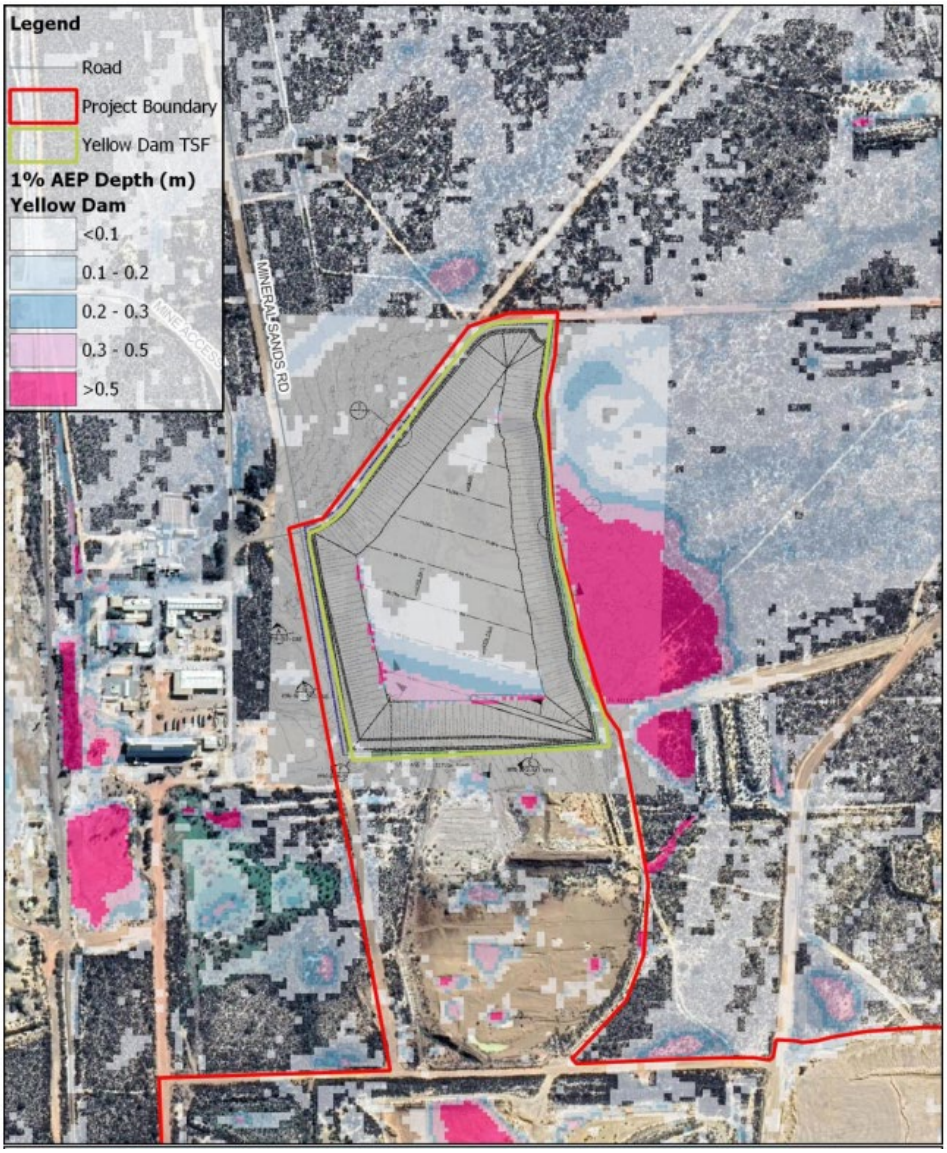


Figure 5: 1% AEP Depth at Yellow Dam TSF

2.3 Part IV of the EP Act

The works approval holder referred the ERER proposal to the Western Australian Environmental

Protection Authority (EPA) on 26 October 2021.

The EPA considers that the likely environmental effects of the proposal are not so significant as to warrant formal assessment under Part IV of the EP Act.

2.4 Department of Mines, Industry Regulation and Safety

2.4.1 Radiological Council WA/ DMIRS

Radiological exposure risks to workers and members of the public are regulated under the *Radiation Safety Act 1975* (RS Act) and the *Mines Safety and Inspection Regulations 1995*, administered by the Radiological Council of Western Australia and DMIRS. The regulation of radiation safety in Western Australian mines is based on national standards and is addressed under Part 16 of the *Mines Safety and Inspection Regulations 1995*. Part 16 of the regulations covers:

- mining and processing of radioactive material;
- use and storage of radiation sources and irradiating apparatus at mines;
- radiation safety for workers;
- requirements to protect the public; and
- radioactive waste management (DMIRS, 2022).

A Radiation Management Plan and associated Radiation Management and Waste Management Plan (RMP; Iluka, 2021) was submitted to DMIRS and the Radiological Council WA for approval in September 2021. The RMP was previously approved in December 2020, for activities associated with Phase 1 and 2 operations (EP1 and EP2) at the Eneabba Mineral Sands Mine and has since been updated to incorporate Phase 3, relevant to this assessment.

The delegated officer notes that approval for the revised RMP has not been granted at the time of issuing the works approval. The applicant will be required to receive approval for the RMP prior to handling EP2 ore concentrate at the ERER.

2.4.2 Native vegetation clearing

The vast majority (approximately 98.6%) of the proposal will be undertaken over cleared land. Although there is no remnant native vegetation required to be cleared, there exists a 5.4 ha area of rehabilitated land.

Approval for the required clearing is being sought via an amendment to approved clearing permit CPS 6915/4. DMIRS is currently assessing the proposed amendment to CPS 6915/4, taking into consideration the presence of Priority fauna (Carnaby's Cockatoo), which forage in the ERER footprint.

No clearing is authorised under the works approval.

2.5 Exclusions to this assessment

The following matters are out of the scope of this assessment and have not been considered within the technical risk assessment detailed in this report:

- preparatory works unrelated to the prescribed activity, such as clearing (refer to section 2.4.2), levelling and construction of access roads, carparks, laydown areas, office buildings, workshops, warehouse/storage, and construction of hardstands for use in construction works;
- vehicle movements on public roads, including transport of products, wastes and potentially hazardous inputs to the ERER;

- closure of the Yellow Dam TSF; and
- occupational exposure to hazards.

The works approval is related to category 44 activities only and does not offer the defence to offence provisions in the EP Act (see s.74, 74A and 74B) relating to emissions or environmental impacts arising from non-prescribed activities, including those listed above.

2.5.1 Progressive closure and rehabilitation

The applicant has a long-term plan to progressively construct and rehabilitate each waste disposal facility as they reach capacity. The construction of additional TSFs at the premises will be subject to separate works approvals. This assessment considers only time limited operations of no longer than 180 days, and the Yellow Dam TSF will be operated for a period well beyond this point (estimated 5.4 years).

Therefore an assessment of closure is beyond the scope of this risk assessment for a works approval, although effective closure of the Yellow Dam TSF is acknowledged as possible at the time of this assessment. Closure of the Yellow Dam TSF may be assessed as part of a subsequent licence amendment, when applied for.

3. Risk assessment

The department assesses the risks of emissions from prescribed premises and identifies the potential source, pathway and impact to receptors in accordance with the *Guideline: Risk Assessments* (DWER 2020).

To establish a risk event there must be an emission, a receptor which may be exposed to that emission through an identified actual or likely pathway, and a potential adverse effect to the receptor from exposure to that emission.

3.1 Source-pathways and receptors

3.1.1 Third party feeds

This works approval has considered in detail the emissions and discharges associated with the refining of rare earth concentrates produced at the Phase 2 Processing Plant (EP2) located at the Eneabba Mineral Sands Mine. The processing of third party concentrates has not been assessed through this assessment to the same level of detail as the characteristics of these materials remains less certain. Changes to ERER feed concentrates may result in a change to the emissions profile from the ERER, particularly seepage from the Yellow Dam TSF, due to differences in the contaminants within the ore concentrate feed and the potential changes to the refining process and reagents required.

It is assumed that alternative feed stocks will have similar characteristics to that from EP2. The applicant has advised that the characterisation of EP2 concentrates presents a conservative representation of contaminants of concern. Any third party feeds that may alter the nature of emissions and/or discharges from that assessed in this report will require reassessment under Part V, Division 3 of the EP Act (refer to 5.1.1).

In-loading of third party ores and occupational exposures

The RMP is considered the primary tool for regulating radioactive materials for the protection of occupational exposure, which is likely greatest at the point of inload of third party concentrates and during pipeline transport within the premises. Controls for the protection of worker exposure are also expected to manage risks to the environment from fugitive dust emissions at inload.

3.1.2 Air Emissions

Atmospheric emissions are generated during the various stages of processing the rare earths (RE) concentrate. Most atmospheric emissions are generated from the roasting and calcination processing stage that need to be captured and treated prior to discharge.

The key emission sources for the operating phase of the ERER are associated with stack emissions from the roaster, calciners, boiler and ammonia scrubber.

A summary of the expected characteristics of the ERER emission sources is presented in Table 3.

Air quality modelling

The expected emissions of key pollutants after treatment alone lead to ground level concentrations that are less than 10% of the assessment criteria, with the exception of the maximum 1-hour NO2 concentration estimated to be approximately 30% of the assessment criteria at the nearest human Receptor 1).

Table 3: Characteristics of emission sources from ERER

Parameter	Unit	Roaster	La_2O_3 calciner	Pr_6O_{11} calciner	Nd_2O_3 calciner	Didymium (NdPr Oxide) calciner	SEGHY* dryer	Ammonia scrubber	Boiler stack
Location	mE	335,931	335,931	335,931	335,930	335,930	335,930	335,584	335,719
	mN	6,692,335	6,692,322	6,692,314	6,692,307	6,692,300	6,692,292	6,692,693	6,692,788
Stack height	m	50	12	12	12	12	12	5	15
Stack internal diameter	mm	750	1250	700	1250	1250	1250	500	800
Temperature	ºC	80	400	400	400	400	120	40	394
Volumetric Flow	Nm^3/h	18,450	8,287	1,719	6,630	8,287	957	5,865	35,652
Exit Velocity	m^3/s	15	6.5	4.3	5.2	6.5	7.8	8.3	12
Emission concentration									
NOx (NO_2 equivalent)	g/s	2.63	7.09	1.47	5.67	7.09	0.14	-	4.84
SO_2		1.02	-	-	-	-	-	-	-
SO_3		0.51	-	-	-	-	-	-	-
H_2SO_4		0.51	-	-	-	-	-	-	-
Particulates (PM_{10} and $PM_{2.5}$)		0.26	0.12	0.02	0.09	0.12	0.01	-	-
Ammonia		-	-	-	-	-	-	0.08	-

*SEGHY - Samarium, Europium, Gadolinium, Heavy Rare Earth Elements and Yttrium

3.1.3 Tailings waste characterisation

The tailings will be pumped as a slurry to the TSF at a solids concentration of approximately 24%, measured by weight. The slurry will be deposited into the TSF by multiple spigots, and it is expected that the residue will consolidate to an initial dry density of approximately 0.99 t/m^3. The particle size distribution of the waste stream ranges between 1.13µm and 211µm with a median size of approximately less than 6.72µm (ANSTO, 2020). By comparison clay particles are typically less than 2µm.

The geochemical abundance index (GAI) of the tailings residue is provided in Appendix 3. The GAI compares the actual concentration of an element in a sample with the median abundance for that element in the Earth crustal abundance. Elemental GAI values above 3 is considered enriched. The ERER tailings sample is enriched with phosphorus, lead, sulfur , zircon, uranium, thorium and rare earth metals. Sulfur, thorium and uranium have the greatest GAI values with an index of 8, 9 and 7 respectively.

A leachate test (Australia Standard Leaching Procedure – AS 4439.3 – 1997) was conducted with the tailings produced in the metallurgical test. All leach tests were carried out using a solid to liquid mass ratio of 1:20 in end-over-end rolled bottle leach tests at ambient temperature for 18 hours. (ANSTO, 2021). Table 4 provides an indication of the concentrations of each contaminant that may leach from the precipitate.

Table 4: Results from waste leachate testing

Parameter	Sample (mg/dry kg)	Concentration		
		pH 2.9 acetate leachate (mg/L)	Borate leachate (mg/L)	Bore water leachate (mg/L)
Ag	<1	<0.001	<0.001	<0.001
Al	1900	<0.01	<0.01	<0.01
As	<1	<0.001	<0.001	<0.001
B	60	0.13	-	<0.05
Ba	57	0.14	0.00072	0.022
Be	0.3	<0.0001	<0.0001	<0.0001
Ca	26,500	2,030	233	590
Cd	5.0	0.0054	<0.0001	<0.0001
Ce	7,100	0.00016	<0.00001	0.00006
Co	2	0.012	<0.001	<0.001
Cr (III +VI)	40	0.006	0.003	0.003
Cu	3	0.002	0.003	0.001
Fe	4,090	<0.05	0.006	<0.005
Hf	2.6	0.00005	0.001	<0.00001
Hg	<10	<0.01	<0.01	<0.01
K	70	0.53	2	<0.01
La	3,700	0.0002	<0.00001	0.0006
Mg	11,400	147	1.1	3
Mn	210	1.0	0.005	0.0010
Mo	<0.1	0.0052	0.001	0.001
Na	2,800	59	N/A[1]	45

Ni	90	0.15	<0.001	<0.001
P	17,700	1.2	<0.01	0.03
Pb	340	0.0002	<0.0001	<0.0001
S	100,700	334	2,050	467
Sb	1.0	0.0004	0.0017	<0.0001
Se	<0.5	<0.0005	<0.0005	<0.0005
Si	5,600	5.7	0.1	1.1
Th	9,240	0.00004	0.00001	0.00001
U	350	0.34	0.00016	0.024
V	14	0.001	<0.001	<0.001
Zn	7	0.039	<0.005	<0.005

Note 1: Borate liquor contains NaOH
Source: ANSTO, 2021

Based on the ERER process, sulfate is expected to be found in the tailings solution at high concentrations. Aluminium is largely precipitated during the neutralisation process, with aluminium, barium, cerium, nickel and lead each leaching in low concentrations under the three tests (ANSTO, 2021).

Purified liquor tests following waste neutralisation indicate that aluminium, uranium and thorium will not be in the liquid component of the tailings waste stream in significant concentrations. The liquor was sampled as having high salt concentrations (Na, 5,179mg/L), calcium (Ca, 1,452mg/L) and sulfate (SO_4, 2,340mg/L as converted from sulfur concentrations) (ANSTO, 2021).

Radiological characteristics of tailings waste

The vast majority of the radioactive isotopes will report to the tailings stream to be disposed of as waste.

The tailings solid waste will contain approximately 350 ppm uranium (U-238) and approximately 9,200ppm thorium (Th-232). The ERER will produce an average 240,000 tpa (maximum of 300,000 tpa) of solids. The individual activity concentrations for tailings are Th-232 (37 Bq/g or 37 MBq/tonne) and U-238 (4.3 Bq/g or 4.3 MBq/tonne). Thorium remains near to undetectable levels in the liquor due to formation of insoluble thorium pyrophosphate (MBS, 2021).

Polonium 210 (Po-210) was found in the three leaching solutions (acetate, borate and bore water) with the maximum concentration was 0.039 Bq/L for the bore water leachate. Radium is poorly soluble in sulfate solutions so extraction in the leach was minimal with the small amount dissolved later re-precipitated in the purification circuit (ANSTO, 2022).

Table 5: Summary of leach test results for radionuclides

Parameter	**Sample (Bq/dry kg)**	**Concentration**		
		pH 2.9 acetate leachate (Bq/L)	**Borate leachate (Bq/L)**	**Bore water leachate (Bq/L)**
Th-232	37,150	0.00016	0.00004	0.00008
Ra-228	32,470	4.4	<0.18	4.0
Th-228	36,850	<0.05	<0.05	<0.05
U-238	4,340	4.2	0.0020	0.30
Ra-226	3,410	<0.10	<0.11	<0.09
Pb-210	4,500	<0.94	<0.89	<1.3
Po-210	4,640	0.0089	0.0009	0.039

Source: ANSTO, 2021

The total activity reporting to the disposal facility will be of the order of 7.4 x 10^{12} Bq per annum, with an activity concentration of 37 Bq/g.

Naturally occurring radioactive materials (NORMs) present within the tailings waste are largely alpha and beta emitters, with no significant gamma radiation, meaning that transfer through the Yellow Dam TSF liner is unlikely. In general, alpha beta emissions have a low penetrative potential and can be contained within the double HDPE lining system and compacted clay base. In addition, the integrity of the liner is expected to be suitable for the low-level radioactive contaminants within the tailings waste. The Journal of Geotechnical and Geoenvironmental Engineering (Tian et. al, 2017) indicated that HDPE geomembranes in contact with low-level waste leachate are estimated to have a total service life of almost 2,000 years.

Seepage modelling

Seepage modelling considered three scenarios to measure the likely impacts of liquid escaping the Yellow Dam TSF:

1) No liner;
2) Full containment, no seepage; and
3) Liner with 20% seepage rate of the unlined scenario (Jacobs, 2021).

As a measure of conservatism, the third scenario was chosen to demonstrate the predicted extent of seepage beyond the Yellow Dam TSF. Sulfate was chosen as the parameter of interest as this was present in high concentrations within the liquor and leachate, and is most likely to present the greatest risk to beneficial use assuming thorium, uranium and metals will not leach over longer time periods.

Under the third scenario, where seepage rates are approximately 20% of an unlined facility, sulfates could be expected to exceed Australian drinking water guidelines (250mg/L) for a period more than 100 years following closure of the Yellow Dam TSF. However, the predicted sulfate concentrations do not exceed livestock groundwater quality guidelines outside the Eneabba Mineral Sands Mine area. As groundwater flows in a general westerly direction, no changes to the groundwater quality are predicted within the Eneabba Water Reserve abstraction point located 5.5 km north of the Project (Jacobs, 2021).

To avoid the ongoing transport of liquor from the Yellow Dam TSF to groundwater beyond the facilities' closure, the majority of liquid within the TSF will be removed and tailings dried as much as practicable. This is expected to significantly reduce the contribution of seepage to groundwater following closure of the Yellow Dam TSF (closure excluded from this assessment – refer to section 2.5).

Key finding: A large proportion of contaminants within the tailings slurry will be precipitated and have demonstrated low leachability through standard leach testing. However, it remains possible that over a longer period of time metals, uranium and thorium present in the high concentrations in the precipitate, could dissolve under low pH, oxidizing conditions present in superficial groundwater 2m below the base of the Yellow Dam TSF.

The delegated officer acknowledges that the actual seepage rate for a double-lined containment facility with leak recovery is likely to be considerably lower than the modelled 20% rate. Therefore seepage rates are anticipated to lie between those assumed for Scenarios 2 and 3 in modelling. The delegated officer notes that proposed liner material for the Yellow Dam TSF is suitable for long term containment of the low-level radioactive waste (Tian et. al, 2017), and for other contaminants identified in Table 4.

Throughout operation of the Yellow Dam TSF, supernatant liquor will be returned to the ERER via floating decant turret and from underdrainage throughout the life of the TSF.

NORMs and other metals may also be transported with seepage through the TSF liner and must be monitored ongoing.

3.1.4 Noise modelling

Noise modelling conducted for the proposal identified that the combined noise from the Eneabba Phases 1, 2 and 3 activities will not exceed Assigned Levels specified in r. 8 of the *Environmental Protection (Noise) Regulations 1997* (Noise Regulations). Table 6 below demonstrates modelled noise levels at 10 residential receptors within 20km of the ERER facility will not exceed Assigned Levels for nighttime hours (35dB) (Talis, 2021).

Table 6: Predicted noise levels (LA_{10})

Sensitive receiver	Modelled cumulative noise level (dB)
R1	15.0
R2	15.4
R3	22.1
R4	23.4
R5	22.2
R6	16.6
R7	12.6
R8	11.6
R9	10.3
R10	8.0
R11	18.2

3.1.5 Receptors

In accordance with the *Guideline: Risk Assessment* (DWER 2020), the Delegated Officer has excluded the applicant's employees, visitors, and contractors from its assessment. Protection of these parties often involves different exposure risks and prevention strategies, and is provided for under other state legislation.

Table 7 and Figure 6 below provides a summary of potential human and environmental receptors that may be impacted as a result of activities upon or emission and discharges from the prescribed premises *(Guideline: Environmental Siting* (DWER 2020)).

Table 7: Sensitive human and environmental receptors and distance from prescribed activity

Human receptors	**Distance from prescribed activity**
Nearest residential premises (Eneabba townsite)	Approximately 6.3 km north of the Yellow Dam TSF (nearest prescribed activity associated with this assessment). Approximately 5.0 km north of the premises boundary
Golf course (recreational receptor)	Approximately 5.7 km north of the Yellow Dam TSF
Brand Highway	Approximately 3.7 km west of application activities
Environmental receptors	**Distance from prescribed activity**
Groundwater	Refer to section 3.1.3.
Groundwater: Public Drinking Water Source Areas	P1 – 4.9 km north of the Yellow Dam TSF P2 – 2.6 km north of the Yellow Dam TSF Eneabba Town Drinking Water Bore located approximately 5.5 km north of the Yellow Dam TSF

Surface water feature (Wetland ID 510) that can be described as a creek line subject to inundation during heavy rainfall periods. The feature is associated with a superficial aquifer although native vegetation is not groundwater dependent, possibly surface water dependent (Iluka, 2022).	Approximately 850 m southwest of the Yellow Dam TSF. There are several ephemeral unnamed watercourses in the vicinity of the project area. These temporary features are depicted in Figure 6 and also represent locations of potential surface water-dependent vegetation.
Nearest groundwater dependent ecosystem (Warradarge Fault Zone)	Approximately 3 km west of the Yellow Dam TSF.
Threatened and/or Priority fauna	Carnaby's Cockatoo (Calyptorhynchus latirostris) present within the ERER project area and close proximity to the proposed Yellow Dam TSF location. There is evidence of cockatoos foraging in the area and roosting at the administrative building, approximately 300m west of the Yellow Dam TSF. There are no permanent surface water features in the vicinity.
Surrounding vegetation Threatened and/or priority flora	The ERER and associated infrastructure is surrounded by vast areas of cleared and partially rehabilitated land with vegetation communities typically in degraded condition. Vegetation in the area is described typically low woodland, shrubland and heaths growing on grey-brown sands. This vegetation is unlikely to intercept or rely upon groundwater. There are a number of Threatened and Priority flora species within the Eneabba Mineral Sands Mine study area although very few have been identified in the ERER development envelope. This is despite intensive flora surveys being conducted in the area. There exists high numbers of Priority 4 vegetation (two significant flora species (*Eucalyptus macrocarpa ssp. elachantha* and *Verticordia aurea*) although these species are well represented beyond the proposed ERER and associated infrastructure.

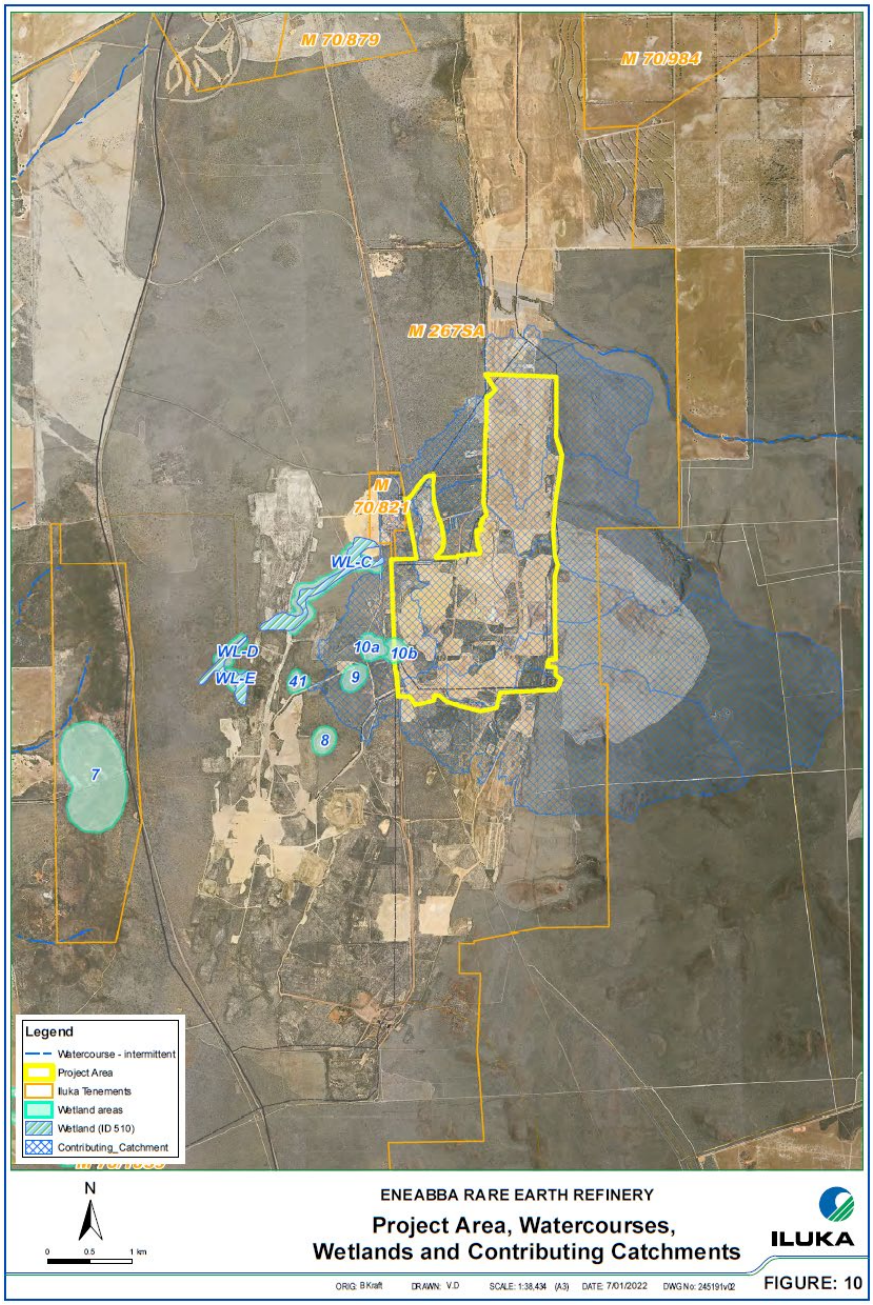


Figure 6: Surface waters and catchment areas

3.1.6 Groundwater

The primary geological units in the area around the ERER proposal area are the Quaternary aged Superficial formations, and the underlying Yarragadee Formation (a high yielding aquifer).

Long term groundwater monitoring has been undertaken at background locations and areas impacted by previous mineral sands mining operations. There has been an observed increase in groundwater levels at a number of groundwater monitoring bores, although this is a result of mine dewatering activities ceasing and groundwater levels recovering to pre-mining levels. Standing water levels at bores EM62, WTE16, WTE17 and WTE01 typically ranged between 30 and 44 metres below ground level following the cessation of groundwater abstraction.

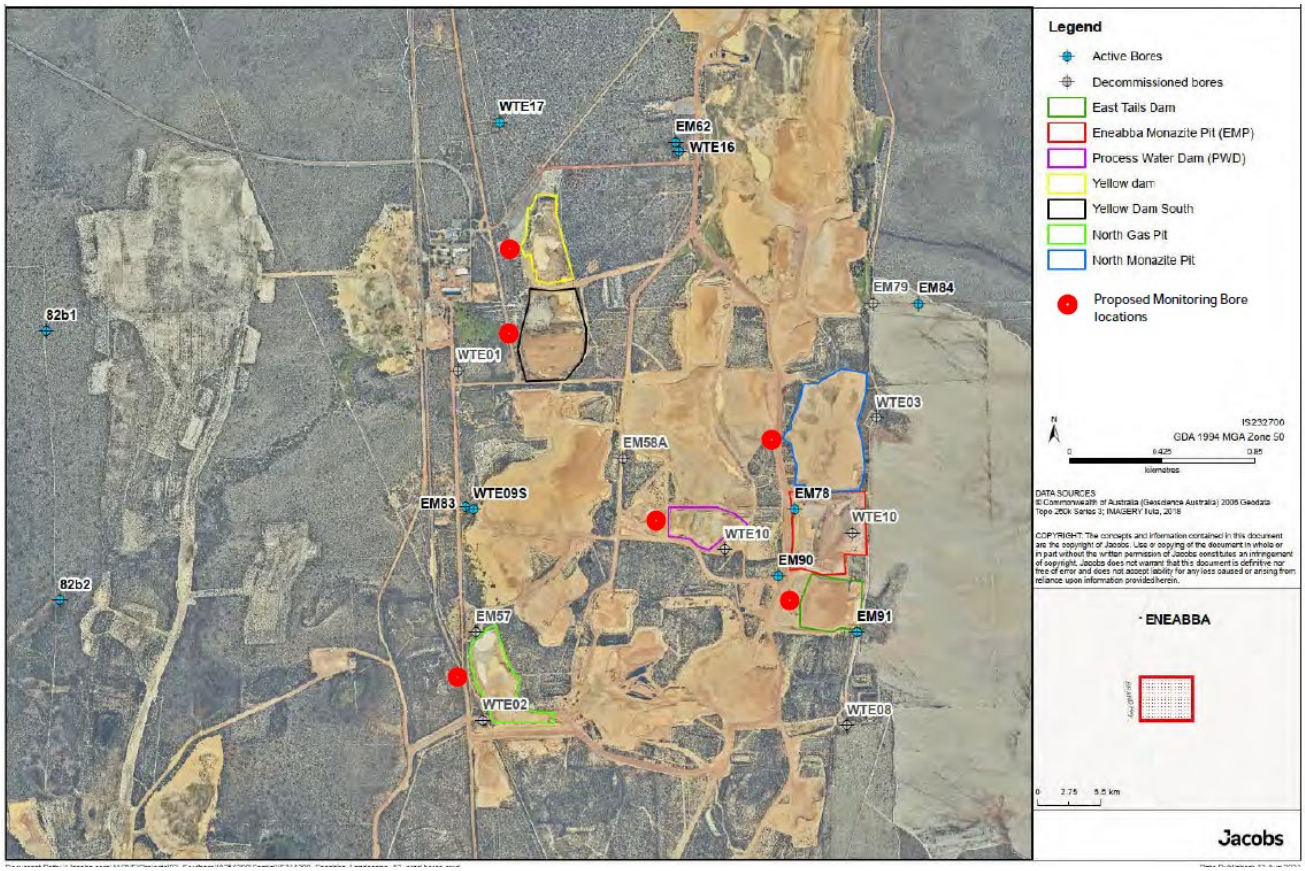


Figure 7: Groundwater monitoring bore locations

Local groundwater is typically neutral to mildly acidic at depth. However, in the perched system, groundwater pH appears to be more acidic, with pH ranging between 4.5 and 5.5. It is possible that the lower pH values in this area may relate to historical mining activities.

Groundwater is fresh to marginally brackish (up to 1,000 mg/L TDS). Although not suitable for human consumption, groundwater has a potential use for agricultural purposes. The presence of nitrogen present as nitrate, and ammonia concentrations below detection locally, groundwater is generally considered oxidizing (Jacobs, 2021).

Local background sulfate concentrations range between approximately 30 and 85mg/L, significantly lower than estimated concentrations in the seepage model for the Yellow Dam TSF (refer to section 3.1.2). An acid sulfate soils (ASS) survey over the Eneabba Operations was conducted in 2008 to identify whether there are any potentially acid sulfate soils (PASS). The assessment determined that no PASS soils are likely to occur within the Eneabba mine site.

Of the contaminants present in the tailings waste stream, lead, cadmium, aluminium and uranium were measured as being below limits of reporting for the groundwater analysis undertaken at the monitoring locations identified in Figure 7 (Iluka, 2022).

Investigations informing the seepage modelling identified that groundwater flows in a west to north-west direction, away from the Eneabba Water Reserve.

3.1.7 Commissioning

Construction is expected to be completed Q1 2025, at which time Environmental Commissioning Activities will commence in Q1 2025. The commissioning phase is expected to be 12 months, at 24 hrs/day, 7 days a week.

3.2 Risk ratings

Risk ratings have been assessed in accordance with the *Guideline: Risk Assessments* (DWER 2020) for each identified emission source and takes into account potential source-pathway and receptor linkages as identified in Section 3.1. Where linkages are in-complete they have not been considered further in the risk assessment.

Where the applicant has proposed mitigation measures/controls (as detailed in Section 3.1), these have been considered when determining the final risk rating. Where the delegated officer considers the applicant's proposed controls to be critical to maintaining an acceptable level of risk, these will be incorporated into the works approval as regulatory controls.

Additional regulatory controls may be imposed where the applicant's controls are not deemed sufficient. Where this is the case the need for additional controls will be documented and justified in Table 8.

Works approval W6641/2022/1 that accompanies this decision report authorises construction, commissioning and time-limited operations. The conditions in the issued works approval, as outlined in Table 8 have been determined in accordance with *Guidance Statement: Setting Conditions* (DER 2015).

A licence is required following the time-limited operational phase authorised under the works approval to authorise emissions associated with the ongoing operation of the premises. A risk assessment for the operational phase has been included in this decision report, however licence conditions will not be finalised until the department assesses the licence application.

Table 8: Risk assessment of potential emissions and discharges from the premises during construction, commissioning and time limited operation

Risk Event					Risk rating Consequence Likelihood	Reasoning	Regulatory controls
Source/ Activities	**Potential emissions**	**Potential pathway and impact**	**Receptors**	**Applicant controls**			
Construction works							
Civil excavation, earthworks, vehicle movements on unsealed roads Earthworks associated with preparation for constructing the process plant and associated infrastructure, Yellow Dam TSF, Brine Bleed Evaporation Pond and Stormwater Dam.	Noise	Air/windborne pathway to residential receptors.	Nearest residential receptors approximately 5km to the north.	No controls proposed.	***Low risk*** Specific Consequence Criteria likely to be met (**Minor**) In exceptional circumstances (**Rare**)	Noise modelling predicts a cumulative noise output from both Eneabba Phase 1 and Phase 2 projects to not exceed 67% of night-time Assigned Levels (L_{A10}). There are expected to be zero exceedances of the Assigned Levels at the nearest noise sensitive receptors during operations.	No conditions for the management of noise during construction. The applicant will be required to comply with the Noise Regulations.
	Fugitive emissions (dust)	Air/windborne pathway to residential receptors. Air/windborne pathway to adjacent environmental receptors that may experience smothering.	Nearest residential receptors approximately 5km to the north.	Use of dust suppression on roads and open areas (water carts, etc.) Vehicle movement and speeds restricted. Cease work in the event of high dust conditions.	***Low risk*** Specific Consequence Criteria met (**Slight**) In exceptional circumstances (**Rare**)	Due to the proximity of the closest residential dwellings (~5km) and position with respect to prevailing east/west winds, there is a 'Low risk' that fugitive dust from construction works during unfavourable weather conditions could impact the amenity of off-site receptors. Applicant controls will ensure that the likelihood of impacts to residential receptors will remain as 'rare' during construction. Nearby vegetation expected to be resilient to the levels of dust generated by earthworks associated with the construction of the ERER facility. Nearby vegetation expected to be well represented in the region.	Consistent with commitments made by the applicant.
	Erosion and sedimentation from surface water runoff	Adverse health impacts to downgradient native vegetation and local ecosystems caused by: • increased volume of stormwater runoff from hardstand areas resulting in erosion; and • overland sediment and/or hydrocarbon runoff from site.	Adjacent vegetation associations. Natural catchments within and adjacent to the premises.	Uncontaminated stormwater diverted away from operational areas to natural downstream drainage to maintain natural surface water flows as much as possible and minimise sedimentation and erosion. Liquid chemicals, including hydrocarbons will be stored in designated areas and on self-bunded facilities.	***Low risk*** Minimal off-site impacts on local scale (**Minor**) Not likely to occur in most circumstances (**Unlikely**)	Altering the natural and local surface water regime may impact on soil replenishment and downstream (off-site) surface water dependent ecology. The delegated officer considers implementation of applicant controls will ensure the risk of adverse impacts to downgradient native vegetation and local ecosystems can be acceptable. As the proposed controls are critical for maintaining an acceptable level of risk, they will be imposed on the works approval.	Consistent with commitments made by the applicant.
Commissioning and time-limited/full operations							
Environmental commissioning of process plant and associated infrastructure, and subsequent operation	Dust emissions associated with RE concentrate and reagent delivery, transfer and storage	Air/windborne pathway to residential receptors and users of nearest public roads resulting in unreasonable interference to health, welfare, convenience, comfort or amenity. Air/windborne pathway to adjacent environmental receptors that may experience smothering and/or contamination.	Nearest residential receptors approximately 5km to the north. Brand Hwy approximately 3.7 km west of application activities Surrounding vegetation	The monazite product from the Phase 2 facility will be pumped directly to the feed circuit of the ERER or stored within containers for delivery. Third party rare earth concentrate will be delivered to the premises via rotating tipping truck or bags that feed through a hooded and drafted hopper, enclosed conveyor system directly into acid mixing tank. Venting at the feed hopper and conveyor uses the kiln off-gas treatment system (see next row below). Produced RE oxides and carbonates from the ERER will be transported in bulka bags and within sealed containers. All ERER operational areas will be over a	***Low risk*** Minimal off-site impacts on local scale (**Minor**) Not likely to occur in most circumstances (**Unlikely**)	The delegated officer considers implementation of these controls will ensure the risk of off-site dust impacts during delivery, transfer and storage of RE concentrate can be acceptable. Proposed controls are required to maintain an acceptable level of risk. Point source (stack) emissions monitoring will be required during commissioning and operation. Due to the low risk associated with particulates to the environment and public health, ambient/background particulate monitoring is not required on the works approval. Revisions to the RMP will require approval by DMIRS (refer to section 2.4.1) prior to handling alternative feedstocks containing NORMs, providing further assurance that risks will be adequately managed at the point of inload. The final rare earth oxides and carbonates product are not considered to be radioactive for transport purposes and will be trucked to Fremantle Port for export (Iluka, 2022).	Consistent with commitments and proposed infrastructure controls in the Application.

Risk Event					Risk rating Consequence Likelihood	Reasoning	Regulatory controls
Source/ Activities	**Potential emissions**	**Potential pathway and impact**	**Receptors**	**Applicant controls**			
				bitumen/concrete/compacted limestone hardstand with vehicle speed restrictions applied. Dust monitoring at background and boundary locations will be conducted using existing dust monitoring devices within the Eneabba Mine site. Pneumatic transfer systems installed with bag filters to remove particulates from conveying air before venting to the environment.			
	Stack emissions during commissioning and testing, and subsequent full operations	Air/windborne pathway to residential receptors and users of nearest public roads resulting in unreasonable interference to health, welfare, convenience, comfort or amenity.	Nearest residential receptors approximately 5km to the north. Brand Hwy approximately 3.7 km west of application activities	Roasting Kiln Off Gas Treatment System consisting of a Venturi Scrubber system, Spray Tower, Wet Electrostatic Precipitator, Mist Eliminator and acid recovery tanks, with cleaned off gas discharge via a stack. Installation of sampling port on main gas treatment stack to allow periodic stack sampling in accordance with the AS 4323.1. Baghouse filter systems or wet scrubbers installed at calciners to remove entrained (fugitive) particulates including a: • dedicated system installed for each process train. • multi-compartment bag house filter to capture fine particulates.	***Low risk*** Specific Consequence Criteria met (**Slight**) Not likely to occur in most circumstances (**Unlikely**)	Gases from the kiln will be cleaned using a flue gas treatment system. The Roasting Kiln Off Gas Treatment System will consist of a Venturi Scrubber system, Spray Tower, Wet Electrostatic Precipitator, Mist Eliminator and acid recovery tanks, with cleaned off gas discharge via a stack. Other point sources will have either bag filters or wet scrubbers installed to manage particulate emissions. Air dispersion modelling (ETA 2021) indicates that with the above controls in place, maximum GLCs for SO_2 and NO_2 (1-hr) and SO_2 (24-hr) are well below the current (2021) NEPM criteria across the model domain when considering emissions (excluding background). There are no industrial activities that might significantly contribute to ambient air quality in Eneabba. To ensure an acceptable level of risk is maintained during commissioning and time limited operations, controls will be imposed on the works approval to require installation of the proposed pollution control equipment. The delegated officer expects that validation of emissions will be conducted during commissioning (stack testing) to ensure emissions meet manufacturer's specifications (Table 3), and at least once during time limited operations. An environmental commissioning report must be submitted following the completion of commissioning. The delegated officer has determined not to impose emission limits on the works approval or subsequent licence at this stage on the grounds the pollution control equipment proposed is appropriate for the risk profile for this type of plant, and predicted emissions are well below the NEPM criterion.	Consistent with applicant-proposed controls and monitoring.
	Radiological emissions associated with: Stack emissions during commissioning and testing, and subsequent full operations Concentrate in-loading to the ERER	As above	Nearest residential receptors approximately 5km to the north. Brand Hwy approximately 3.7 km west of application activities	Implementation of approved Radiation Management Plan. Compliance with Mines Safety and Inspection Regulations regarding radiological risks.	N/A	The concentrate feed will exhibit elevated levels of NORM and will require management via the approved RMP for compliance with the Mines Safety and Inspection Regulations. The RMP outlines guideline exposure levels for employees, internal investigation levels, annual anticipated radiation dose assessments for specific work groups, and methods for minimising exposure. Radiological risks to workers and the community are regulated under the RS Act and *Mines Safety and Inspection Regulations 1995*, administered by the Radiological Council of Western Australia and DMIRS. Regulation of impacts to workers is expected to also protect environmental receptors.	Not applicable.
	Noise associated with plant operation during commissioning and testing, and	Air/windborne pathway to residential receptors resulting in unreasonable interference to comfort or amenity.	Nearest residential receptors approximately 5km to the north.	No controls proposed due to large separation distance to receptors.	***Low risk*** Specific Consequence Criteria met (**Slight**) In exceptional	Noise modelling predicts a cumulative noise output from both Eneabba Phase 1 and Phase 2 projects to not exceed 67% of night-time Assigned Levels. There are expected to be zero exceedances of the Assigned Levels at the nearest noise sensitive receptors during operations.	No noise controls applied to the works approval.

Risk Event					Risk rating Consequence Likelihood	Reasoning	Regulatory controls
Source/ Activities	**Potential emissions**	**Potential pathway and impact**	**Receptors**	**Applicant controls**			
	subsequent full operations				circumstances (**Rare**)	The delegated officer considers that full compliance with the Noise Regulations can be achieved without additional controls applied through the works approval or licence.	
Containment of tailings waste, recovered process water and RO brine water	Loss of containment of tailings, process water or brine water from storage ponds, dams and delivery pipelines	Groundwater flows in a westerly to north-westerly direction. Seepage/infiltration causing groundwater contamination and impacts to non-groundwater dependent ecosystems.	Groundwater >20mbgl at the Yellow Dam TSF, Brine Bleed Evaporation Pond and Process Water Dam. Groundwater dependent ecosystems located approximately 3 km west of the Yellow Dam TSF. Surface water/perched aquifer dependent ecosystems located approximately 850 m west. Adjacent priority vegetation.	Each pond lined to the specifications defined in Table 2. Under liner leak detection system will be installed at the Yellow Dam TSF to confirm the ongoing integrity of the liner system. Management of the pond to improve water recovery through a decant turret system and tailings beach management during spigot deposition. Decant water will be pumped to the ERER Return Water Tank before being transferred to the ERER facility.	***Medium risk*** Mid-level impacts on local scale (**Major**) Will probably not occur in most circumstances (**Unlikely**)	Proposed controls for seepage at the Yellow Dam TSF, primarily the double liner with compacted clay base, leakage collection and detection system, sufficiently manage the risk of seepage of tailings. Seepage modelling assumes a 'worst case scenario' for the lined facility to have a leakage rate equivalent to 20% of the rate calculated for an unlined TSF. Groundwater monitoring will be required to ensure seepage does not result in unacceptable impacts to groundwater, groundwater dependent ecosystems or other native vegetation receptors. Routine liner leak detection tests will also be required on the licence, to provide assurance over the integrity of the ponds. The Brine Bleed Evaporation Pond will be constructed with a single 1.0mm HDPE liner. Depth to groundwater at the ERER facility is approximately 20 mbgl. Stormwater Dams (2) will be HDPE-lined, which minimises the overall risk of potentially contaminated stormwater reaching groundwater through fugitive seepage across the premises or at the pond locations. Stormwater containment presents a lower risk to other containment facilities due to predicted lower contaminant concentrations to other ponds at the premises. The delegated officer has determined that the proposed liner and management controls, along with regular groundwater monitoring, will result in an acceptable level of risk to the environment. As this determination is based on proposed controls being implemented as critical controls, they will be imposed on the works approval, and required to be maintained on the licence and minimum infrastructure requirements.	Consistent with applicant-proposed controls and monitoring. Further conditioning to require that liner specifications must comply with WQPN #26 (DoW 2013) requirements. In addition for the Yellow Dam TSF construction and operation to be overseen by a geotechnical expert (refer to section 4.1.1).
		Overtopping or containment failure causing adverse impacts to downgradient native vegetation and local ecosystems Flow of potentially contaminated surface water beyond the ERER project area.	Surface water/perched aquifer dependent ecosystems located approximately 850 m west. Adjacent priority vegetation.	TSF, process water and brine evaporation ponds all designed with sufficient capacity to account for 1:100 year, 72-hour AEP storm event. Operational freeboard 500 mm at the Yellow Dam TSF, brine evaporation and process water ponds. TSF supernatant pond will be managed using floating turret decant system that abstracts water and returns it to the ERER Return Water Tank. The tailings beach and pond size/location managed through rotating spigot deposition. Tailings pipelines equipped with automatic cut-outs in the event of pipe failure, blockage or leak, as detected by pressure sensors. Pipelines will be located within earthen bunded corridors across existing disturbed areas. Daily inspections and integrity checks of ponds and pipelines when operational. Surface water flows diverted around the TSF using bunding and drains to prevent the ingress of uncontaminated stormwater.	***Medium risk*** Mid-level impacts on local scale (**Major**) In exceptional circumstances (**Rare**)	The proposed storage facilities have been designed with sufficient capacity to account for a significant rainfall event. The ERER has greater water requirements than what can be abstracted through decant from the Yellow Dam TSF (Figure 4). The delegated officer considers these controls will ensure the risk of impacts from overtopping is acceptable. As the proposed controls are critical for maintaining an acceptable level of risk, they will be imposed on the works approval, and required to be maintained on the licence and minimum infrastructure requirements.	Consistent with applicant controls. ERER Return Water Tank required to be installed with high-level alarms to prevent overtopping.
	Radiological emissions from	Air/windborne pathway to residential	Adjacent priority	Implementation of dust control measures, including the management of tailings such	***Medium risk***	Tailings and waste liquor from the ERER that will report to the TSF contains naturally occurring radioactive materials at concentrations	Consistent with applicant-proposed

Risk Event					Risk rating Consequence Likelihood	Reasoning	Regulatory controls
Source/ Activities	**Potential emissions**	**Potential pathway and impact**	**Receptors**	**Applicant controls**			
	tailings waste and/or liquor at the Yellow Dam TSF, including dust and electromagnetic radiation.	receptors and users of nearest public roads resulting in unreasonable interference to health, welfare, convenience, comfort or amenity. Air/windborne pathway to adjacent environmental receptors that may experience smothering and/or contamination. Fauna access/exposure and potential entrapment leading to injury or death.	vegetation. Terrestrial fauna Migratory birds	that moisture is maintained to prevent dust emissions. The average water level above the tailings will be maintained at approximately 1m. A supernatant pond covering approximately 90% of the Yellow Dam TSF during tailings deposition. Storage facilities and ponds constructed with liner in accordance with Table 2 over a compacted clay material. Under liner leak detection system will be installed at the Yellow Dam TSF. The perimeter of the TSFs will be fenced during operations to restrict fauna access. The TSF will be inspected, twice daily to ensure birds are not present at the TSF.	Mid-level impacts on local scale (**Major**) Will probably not occur in most circumstances (**Unlikely**)	exceeding the recognised level for radioactive classification (specific activity Th-232 of 37Bq/g and U-238 of 4.3Bq/g), and therefore the waste is classified as radioactive. The delegated officer notes that proposed liner material for the Yellow Dam TSF is suitable for long term containment of low-level radioactive waste (Tian et. al, 2017). There is an inherent risk of airborne dust, including dust containing NORM, to be generated from the tailings beach during dry and windy conditions, where it can cause adverse impacts to nearby human and environmental receptors. Implementation of dust management controls proposed by the applicant, including the proactive management of tailings moisture and maintenance of a supernatant pond over approximately 90% of the Yellow Dam TSF, is expected to minimise the risk of unacceptable impacts. As the proposed controls for electromagnetic radiation and containment of tailings containing NORMs are critical for maintaining an acceptable level of risk to environmental receptors. Therefore they will be imposed on the works approval and required to be maintained on the licence and minimum operational requirements. Radiological risks will also be managed via the approved RMP for compliance with the Mines Safety and Inspection Regulations. The RMP outlines guideline exposure levels for employees, internal investigation levels, annual anticipated radiation dose assessments for specific work groups, and methods for minimising exposure. Controls for the protection of human health, regulated under the RS Act, and *Mines Safety and Inspection Regulations 1995,* are also expected to be protective environmental receptors. Conditions for the management of radioactive waste material have only been applied where they are for the protection of environmental receptors. The delegated officer notes that the Yellow Dam TSF is unlikely to provide a suitable water source for fauna due to the high salinity and sulfate levels of the supernatant liquor. There exist other suitable water sources nearby, at greater distance from industrial activity and of better quality, that are more likely to be targeted.	controls. Radiological risks to human receptors (personnel and public) are adequately regulated under the RS Act, and *Mines Safety and Inspection Regulations 1995* administered by the Radiological Council of Western Australia and DMIRS.
Hazardous materials including reagents and hydrocarbon storage	Spills and leaks of hazardous materials, including reagents, and hydrocarbons	Overland runoff from site, causing adverse health impacts to downgradient native vegetation and local ecosystems. Soil contamination, limiting the potential for vegetative rehabilitation. Seepage to groundwater.	Priority vegetation. Intermittent wetland approximately 1.2km to the southwest. Groundwater located approximately 20 mbgl.	All diesel stored within One 110,000 L self-bunded, horizontal above-ground tank situated on an earthen pad. Designed and manufactured to AS1940. Large (>100 tonnes) reagent stores will be within purpose built bunded tanks. Smaller stores will be within bulk boxes or bags on a bunded hardstand area. All reagents storage in accordance with Australian Standards AS1940, AS 3833 or AS3780. Spill kits located at hydrocarbon and reagent storage areas. No major equipment servicing undertaken on-site. Refuelling will be via service trucks and will be manned during refuelling Bunded areas contain sump to recover spilled liquid and rainfall. Recovered liquid to be treated and reused in process.	***Low risk*** Low level onsite impacts (**Minor**). In exceptional circumstances (**Rare**)	The delegated officer notes that existing Priority 4 vegetation to the chemical storage areas is regrowth that will be cleared in accordance with CPS 6915/4. Therefore the nearest environmental receptor is approximately 1.2 m to the southwest (P4 vegetation and intermittent wetland). All hazardous materials and hydrocarbons will be stored within bunded areas consistent with AS 1940, with spilled liquid and rainfall to be recovered and/or captured in Stormwater Ponds (2) and reused in the process. The delegated officer considers these controls will ensure the risk of impacts from spills and leaks from bulk hazardous and hydrocarbon storage areas remains low. The low risk is determined based on proposed containment infrastructure being constructed (bunding and site stormwater management). Therefore these controls will be imposed on the works approval and required to be maintained on the licence as minimum infrastructure requirements.	Consistent with applicant-proposed controls.

Risk Event					Risk rating Consequence Likelihood	Reasoning	Regulatory controls
Source/ Activities	**Potential emissions**	**Potential pathway and impact**	**Receptors**	**Applicant controls**			
	Contaminated surface water runoff from operational areas	Overland runoff from site, causing adverse health impacts to downgradient native vegetation and local ecosystems.	Priority vegetation. Intermittent wetland approximately 1.2km to the southwest.	Surface runoff within plant footprint will be contained within stormwater retention basin with capacity to contain 1:100 year, 72 hour storm event. Two stormwater dams with a nominal size of 13,000 m^3 used to capture any rainwater runoff from site for reuse in the ERER plant.	***Low risk*** Minimal offsite impacts at a local scale (**Minor**). In exceptional circumstances (**Rare**)	To minimise potential impacts to off-site surface water systems and native vegetation, the applicant has designed the site for zero discharges, with runoff from the plant footprint collected and reused in the process following treatment, and clean stormwater runoff directed to two stormwater ponds with capacity to contain a 1% AEP flood event (equivalent to the 1:100 year ARI). Captured water will be reused in the ERER process. The delegated officer considers these controls will ensure the risk of impacts from contaminated surface water runoff is acceptable. As the proposed controls are critical for maintaining an acceptable level of risk, they will be imposed on the works approval, and required to be maintained on the licence and minimum infrastructure requirements.	Consistent with applicant-proposed controls.
Closure							
Yellow Dam TSF closure	Radiological emissions (dust) from dried tailings containing NORMs	Air/windborne pathway to residential receptors and users of nearest public roads resulting in unreasonable interference to health, welfare, convenience, comfort or amenity. Impacts to rehabilitation potential where revegetation is not able to establish. Failure to establish vegetative habitat may restrict local fauna populations.	Priority vegetation. Carnaby's Cockatoo	Supernatant water will be removed as far as practicable, and tailings dried. Minimum 4m capping layer will be applied to the surface of the Yellow Dam TSF, including: • Growth medium or topsoil 3 m (minimum). • Secondary fill material (subsoil layer) 0.6 m (minimum). • Geotextile (nonwoven polyester). • Drainage and inadvertent intrusion prevention layer (gravel / fragmented / concrete rock or equivalent) 0.5 m (minimum). • Geotextile (nonwoven polyester). • Geomembrane – 0.4 to 0.6 mm Linear Low-Density Polyethylene (LLDPE). • Multi linear drainage geo-composite layer. • Additional fill material to create the final landform shape above the tailings.	N/A	Closure of the Yellow Dam TSF is beyond the scope of construction, commissioning and time-limited operations. Further consideration will require input from DMIRS and assessment at the time of licence application.	No conditions on the works approval for controls at the time of closure. The delegated officer will consider the need for Yellow Dam TSF closure requirements (capping) at the time of licence assessment. Radiological risks to human receptors (personnel and public) are regulated under the RS Act, and *Mines Safety and Inspection Regulations 1995* administered by the Radiological Council of Western Australia and DMIRS.
	Loss of containment of tailings	Infiltration of rainwater into the disposed tailings waste and then seepage to groundwater resulting in ongoing migration of contaminants in groundwater.	Groundwater dependent ecosystems located approximately 3 km west of the Yellow Dam TSF. Surface water/perched aquifer dependent ecosystems located approximately 850 m west. Adjacent priority vegetation.				

Note 1: Consequence ratings, likelihood ratings and risk descriptions are detailed in the *Guideline: Risk Assessments* (DWER 2020).

Note 2: Proposed applicant controls are depicted by standard text. **Bold and underline text** depicts additional regulatory controls imposed by department.

4. Consultation

Table 9 provides a summary of the consultation undertaken by the department.

Table 9: Consultation

Consultation method	Comments received	Department response
Application advertised on the department's website on 17 February 2022.	None received	N/A
Local Government Authority (Shire of Carnamah) advised of proposal on 28 April 2022	The Shire of Carnamah acknowledged its support of the proposal. No additional comments provided.	N/A
Department of Mines, Industry Regulation and Safety (DMIRS) advised of proposal 28 January 2022.	Refer to section 4.1.1	The delegated officer notes the position of DMIRS. Although the acceptance of third party concentrate feeds may be acceptable, further information is required on the subsequent emissions and discharges associated with alternate feeds. This is consistent with DMIRS approach.
Department of Biodiversity, Conservation and Attractions (DBCA) advised of proposal on 28 January 2022	No comments received.	N/A
Applicant was provided with draft documents on 18 May 2022.	Refer to Appendix 1	Refer to Appendix 1

4.1.1 DMIRS

As the proposal exists within a State Agreement area, approval of a Mining Proposal is not required. Therefore DWER sought advice and recommendations from DMIRS on the design of the Yellow Dam TSF with a view to confirm geotechnical stability of the facility.

In addition, DMIRS is responsible for ensuring the applicant's compliance with Part 16 of the *Mines Safety and Inspection Regulations 1995* with support from the Radiological Council.

Stability and seepage

DMIRS provided a number of recommendations in relation to confirming geotechnical stability of the Yellow Dam TSF including:

- Annual TSF third party audits are undertaken.
- Standard tenement conditions generally applied under the Mining Act be used for the TSF.

Information gaps identified by DMIRS in relation to stability have since been resolved by the applicant and considered in this risk assessment, including the management and diversion of surface waters away from the Yellow Dam TSF and suitable alternatives if materials cannot be sourced locally. For example, the applicant has confirmed that where a local clay source is not identified a geosynthetic clay liner will be utilised (Iluka, 2022a).

An understanding of tailings consolidation from bench scale tests was also unavailable at the time of referral. The applicant has advised that conservative settling rates have been based on equivalent material from the applicant's North Capel concentrate plant, which has a precipitate with similar physical properties.

ANSTO settling and consolidation testing of precipitates from the North Capel concentrate plant are continuing at the time of assessment. Results from this testing is expected to validate capacity assumptions used in the TSF design.

Based on the environmental risk due to containment of NORMs, DMIRS recommend annual third party TSF audits are undertaken during the operation of the Yellow Dam TSF. To prevent slipping of the Yellow Dam TSF lining system, quality assurance and control procedures have also been recommended with installation oversight required by Geotechnical engineer.

DMIRS also raised interest in the Yellow Dam TSF design in relation to structural integrity impacts from the Yellow Dam South TSF, which is not currently required or applied for, but will be adjacent to the proposed facility. Although beyond scope of this assessment, any future works nearby that may have the potential to impact the structural integrity of the Yellow Dam TSF will need to be reviewed by a geotechnical engineer and referred to DMIRS as the lead agency with geotechnical expertise.

Radiological aspects

At the time of assessment DMIRS advised DWER that the acceptance of third party ores cannot be approved based on the submitted RMP, as the characterisation of alternate product streams has not been provided. The final RMP is currently under assessment by DMIRS and the Radiological Council. The RMP is considered the primary tool for regulating radioactive materials for the protection of occupational safety.

DMIRS reviews RMP submissions through the lens of protection of worker health and safety and ensuring that potential radiation doses to workers and members of the public are maintained "as low as reasonably achievable". With regards to the containment of radioactive materials, DMIRS has identified that the design of the Yellow Dam TSF base is sufficient to prevent the emission of radioactive emitters. However, there remains the possibility that where liquor is able to pass the containment liner system, soluble radioactive materials may also be transported with that seepage.

DMIRS noted the high concentrations of uranium and thorium in the precipitate, although this is likely to be contained in the TSF in solid form. Therefore DMIRS has recommended the inclusion of radioactive isotopes uranium, thorium and radium in the monitoring of groundwater downstream of the Yellow Dam TSF. In addition, tracer/indicator elements such as barium and calcium should be monitored as they have similar chemical behaviours to radium, which may dissolve within the facility or groundwater over time, under oxidizing and low pH conditions.

Acid mixing during the process reduces the pH of the concentrate to levels that may dissolve radium, which emits gamma radiation. As described in section 3.1.3, it is likely that based on ANSTO characterisation studies, radium is not expected to be soluble in sulfate solutions, such as those in the acid mixing stages.

Once mining operations cease, the premises will remain registered under the *Radiation Safety Act 1975* until the registration is terminated by the Radiological Council.

5. Conclusion

Based on the assessment in this decision report, the delegated officer has determined that a works approval will be granted, subject to conditions commensurate with the determined controls and reporting requirements necessary for administration. The delegated officer has determined that the proposal does not pose an unacceptable risk of impacts to public health or the environment. This determination is based on the following:

- the location of the proposal having sufficient separation to community receptors such that air quality (NEPM) and noise standards will be complied with, even when considering all noise sources and the highest night-time propagation weather conditions;
- emissions from radioactive materials at refining locations will be regulated under Part 16 of the *Mines Safety and Inspection Regulations 1995*, through implementation of a Radiation Management Plan once approved by DMIRS and the Radiological Council. Regulation for the protection of worker and public health are expected to also protect the environment; and
- the controls proposed for the containment of ERER byproducts and treatment of off-gases significantly reduce risks to acceptable levels and are conditioned on the works approval as critical controls.

5.1.1 Third party feeds

For reasons detailed in section 3.1.1, the delegated officer has elected to authorise the construction of third party concentrate in-loading infrastructure, as well as handling and processing. However, approval to receive and process alternative concentrates may need to be sought on a case-by-case basis via future licence amendments in the event that the nature of wastes is altered in accordance with s. 53 of the EP Act, which states:

"Subject to this Act, the occupier of any prescribed premises who, if to do so may cause an emission, ***or alter the nature or volume of the waste****, noise, odour or* ***electromagnetic radiation emitted, from the prescribed premises… [must do so] in accordance with a works approval or licence****…commits an offence unless he does so — in accordance [with a works approval or a licence…]"*

The delegated officer acknowledges that the applicant has committed to revising the RMP, to incorporate feed blends as relevant to the operational period. Further that third party feed materials will be of lower uranium and thorium activity concentrations than that of EP2 Monazite concentrate (Iluka, 2021). To ensure continued compliance with s.53 of the EP Act, the delegated officer has determined that information on product characteristics must be obtained and available to DWER upon request.

5.1.2 Radiological risks

In its current state, the focus of controls under the RMP is for the protection of public and worker safety, as opposed to the protection environmental values although they too are considered. The delegated officer notes that conditions of the works approval for construction and time limited operations do not to contradict, or unnecessarily duplicate any requirement under the *Mines Safety and Inspection Regulations 1995* for radiological material management.

Each control for the containment of radioactive materials within the Yellow Dam TSF are also controls for other contaminants of concern, that have the potential to impact groundwater quality. In addition, controls for the scrubbing and filtering of extracted air within the ERER, are required for radioactive and non-radioactive materials. Therefore these controls a considered by the delegated officer to be necessary.

The RMP in its current draft remains silent on the regular monitoring of the Yellow Dam TSF for fauna interaction, in particular by Carnaby's Cockatoos. During the assessment process the applicant committed to daily inspections to ensure that fauna are not exposed to contaminants of concern within the storage facility. The delegated officer has determined that fauna interactions at the Yellow Dam TSF can be managed and monitored under Part V works approval and licence conditions. This supports the objectives of regulation under the *Mines Safety and Inspection Regulations 1995*.

DWER has discussed with DMIRS the need for regular groundwater monitoring of radioactive

isotopes, uranium, thorium and radium. Protection of groundwater values can be regulated under Part V of the EP Act for all contaminants of concern.

5.1.1 Geotechnical stability

In the absence of a Mining Proposal being required for the ERER Yellow Dam TSF, the delegated officer has determined it necessary to incorporate standard requirements for the management of stability for in-pit TSFs that would otherwise be applied under the *Mines Safety Act 1994*. This includes the frequent oversight of a geotechnical engineer throughout construction and time limited operations of the facility, and general TSF design requirements.

5.1.2 Monitoring

Monitoring bores are strategically located both up hydrological gradient and downstream of TSF. Downstream bore locations have been selected in close proximity and at greater distance from the TSF, between the TSF and Warradarge Fault Zone 3km to the west, to ensure impacts can be identified as early as possible, and corrective actions can be implemented. Both shallow and deep screens on monitoring bores are necessary to determine impacts to perched and deeper groundwater.

Water return to the ERER via supernatant abstraction and underdrainage is a key control for preventing seepage from the Yellow Dam TSF and migration of dissolved metals and sulfates. The applicant has identified a targeted average water return of 66% from the Yellow Dam TSF in water balance calculations (CMW, 2021). Water will be returned to the ERER from other collection areas including the Process Water Dam and Stormwater Ponds.

Air emissions monitoring will be required during commissioning of the ERER to ensure consistency with emission rates used to inform this risk assessment. During operations, monitoring will be required at least annually to confirm effective ongoing operation of the Off-Gas Treatment System. Conditions for ongoing monitoring during operation of the ERER will be through a subsequent licence amendment for the overall Eneabba Mineral Sands Mine to incorporate EP3.

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Appendix 1: Summary of applicant's comments on risk assessment and draft conditions

Condition	Summary of applicant's comment	Department's response
Throughput limit specified	20,000 tonnes to 25,000 tonnes The ERER plant is expected to have a rare earth concentrate feed rate of up to approximately 65,000 tonnes per annum (tpa) to produce ~~*up to*~~ *approximately* 25,000 tpa	Increased throughputs are accepted noting the revised water balance for the Yellow Dam TSF and the water demands of the ERER plant. Note that the specified throughput is considered a licence limit is for the purpose of production. Any increase beyond the specified throughputs will require reassessment of risks and amendment.
Infrastructure requirement – ERER processing infrastructure to be constructed as fully enclosed system operating under negative pressure	It is not possible to fully enclose all the processing infrastructure. Only those areas where air emissions are expected will be enclosed and will incorporate emissions management systems.	Noted and accepted.
Yellow Dam TSF liner installation requirements	Request replacing liner testing requirement at welds and joints: ~~*"All seams and joins must be constructed and tested as watertight over their full length using a vacuum box test and air pressure test"*~~ *"All welded seams and joins are tested at selected locations using a vacuum box test, air pressure test, or similar, as per manufacturers QA/QC procedure."*	Noted and accepted.
Accepting feeds from third parties	Remove restrictions on accepting third party concentrate feeds. The refinery has been designed based on the highest radiological case expected for the refinery operations. Any significant increase in the radiological parameters expected will require resubmission of the Radiation Management and Waste Management Plan.	Accepted. See Department's response to applicant comments on the Decision Report in relation to third party feeds.
Brine Bleed Evaporation Pond storage requirements	Request replacing capacity requirements for the Brine Bleed Evaporation Pond: ~~*"Maintain sufficient capacity in the pond to accommodate a 1 in 100 year*~~	Accepted.

Condition	Summary of applicant's comment	Department's response
	~~*rainfall event."*~~ *"Evaporite within the Brine Bleed Evaporation Pond periodically removed to maintain storage capacity following 1 in 100 year rainfall event."*	
Yellow Dam TSF	The underdrainage system may be installed if required by the detailed design.	Noted. Underdrainage at the Yellow Dam TSF was proposed through the original application and has been considered a critical control for the management of seepage risks. Conditions requiring the installation and operation of underdrainage infrastructure has been retained.
Comment on the Decision Report		
Comment in Decision Report to provide demonstration of clearing permit approval	The clearing permit is currently under assessment. No clearing related works on-site will commence until the clearing permit is approved. The status of this approval should not restrict the issuing of the works approval. Particularly given the majority of the site is cleared and will not be subject to the clearing permits.	Noted and accepted. The works approval does not authorise clearing. The applicant will be required to await approval of a clearing permit from DMIRS before any native vegetation is removed.
Exclusions to the assessment – general	The existing Eneabba licence allows a number of the activities above to be undertaken.	Noted. The scope of this Decision Report and works approval is limited to the ERER plant.
Exclusions to the assessment – Excluding third party feeds from being accepted and processed at the ERER Plant	Iluka does not agree that third party feed sources will have any material adverse changes to emissions profile. The Phase 2 feed scenario considered in the Works Approval application, considers tailings with the highest radioactivity and geochemical properties, possible. Incorporation of third party feed sources will result in higher volumes of tailings (due to the lower concentrations of REs in the feed material) and therefore lower radioactivity and geochemical properties than the Phase 2 feed. We therefore request this statement and the similar analysis that follows is reconsidered. The air emissions considered in the application will not change as a result of a change in the feed material, as the off-gas scrubber system is designed to meet the emissions concentrations included in Table 5-1 of the Eneabba Mineral Sands Phase 3 Air Quality Assessment (ETA 2021). In addition, a change in the characteristics of the feed material will not change the liner, management controls or groundwater monitoring. Groundwater monitoring included in the works approval covers all possible parameters within the feed material that can be processed by the refinery.	Accepted. The condition has been removed on the basis of the applicant's confirmation that if risk changes, Iluka will notify DWER in accordance with s.53 of the EP Act. Any potential or future risk arising from increases in the presence of hazards from new concentrate feeds accepted and handled would trigger the requirement for the Licence Holder to notify DWER ahead of accepting that concentrate. In the event of the risk profile changing as a result of handling alternative concentrate feeds, re-assessment will be required to ensure that existing infrastructure, emissions management and environmental monitoring is suitable and specific to the emissions and discharges from the refining of new concentrates and disposing the associated wastes. In making this decision, the delegated officer has taken into consideration the nature of the existing concentrate feed against the low likelihood of third party feeds containing contaminants in greater concentrations. In addition, the controls and monitoring proposed and applied to the works

Condition	Summary of applicant's comment	Department's response
	Therefore, the determination of the delegated officer that there is an acceptable level of risk to the environment, will not change as a result of a change in feed material.	approval are expected to adequately address risks associated with emissions and discharges associated with most feed materials.
	The delegates view appears to be that all third-party feeds will require a licence amendment application, irrespective of the characteristics of that feed and irrespective of the existing controls that would prevent emissions from the prescribed premises entering into the environment. The applicant considers that in accordance with s53 of the EP Act, a licence amendment application should only be required if the third-party feed results in an increase in volume or altered (heightened risk) emissions from the prescribed premises into the environment to that authorised and assessed. This is consistent with a risk-based approach to assessments and condition setting and is consistent with recent advice provided by DWER to other licence holders. Iluka does not consider there is any basis under section 53 for any and all third party feeds to trigger a licence amendment.	As above.

Appendix 2: Eneabba TSF Residue Geochemical Abundance Index (GAI)

	TSF Residue (%)*	Average Crustal Abundance (%)#	Geochemical Abundance Index (GAI)^
Al	0.07	8.2	0
Ca	4.9	4.1	0
Cr	0.001	0.01	0
Fe	4.1	4.1	0
Hf	0.004	0.0003	3
Mg	1.1	2.3	0
Mn	0.01	0.095	0
Na	0.28	2.3	0
Ni	0.009	0.008	0
P	1.8	0.1	4
Pb	0.03	0.0014	4
S	10	0.035	8
Si	0.56	28.2	0
Ti	0.24	0.565	0
Zr	0.31	0.0165	4
U	0.04	0.00024	7
Th	0.92	0.0012	9
La	0.37	0.0039	6
Ce	0.71	0.00665	6
Pr	0.08	0.00092	6
Nd	0.29	0.00415	6
Sm	0.03	0.000705	5
Eu	<0.01	0.0002	-
Gd	0.03	0.00062	5
Tb	<0.01	0.00012	-
Dy	0.01	0.00052	4
Ho	<0.01	0.00013	-
Er	<0.01	0.00035	-
Tm	<0.01	0.000052	-
Yb	<0.01	0.00008	-
Lu	<0.01	0.00008	-
Y	<0.01	0.0033	-

* - Sourced from ANSTO 2021 "Waste Treatment for Eneabba Project"

- CRC Handbook of Chemisty and Physics 92nd Edition - Abundance of Elements in the Earth's Crust and in the Sea.

^ - The GAI was developed by Förstner et al (1993), and is defined as: GAI = log2 [Cn/(1.5 x Bn)] where:

Cn = measured content of n-th element in the sample.

Bn = "background" content of the n-th element in the sample.