

Using Alpha Recoil as a Tool for
Contamination Control in the Khan River
Aquifer (technical report)



Effective date	30/04/2015
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Abstract

Seepage control measures are employed by Rössing Uranium in order to prevent water contaminated by uranium from the extraction process reaching the Khan River aquifer. These controls include seepage recovery and a system of trenches designed to prevent onward flow of contaminated water.

An effective monitoring technique is to measure the specific activities of uranium decay chain radionuclides at monitoring boreholes across the mine site, using the radioactivity ratio of two different uranium isotopes to determine if sampled water is contaminated by freshly extracted uranium or only contains uranium naturally occurring in the water. This monitoring programme is carried out by Rössing Uranium on an annual basis to verify the absence of uranium contamination in the nearby Khan River aquifer. Monitoring results and their analysis are reported to the National Radiation Protection Authority on an annual basis.

Acronyms and abbreviations

The following acronyms and abbreviations are used in this report:

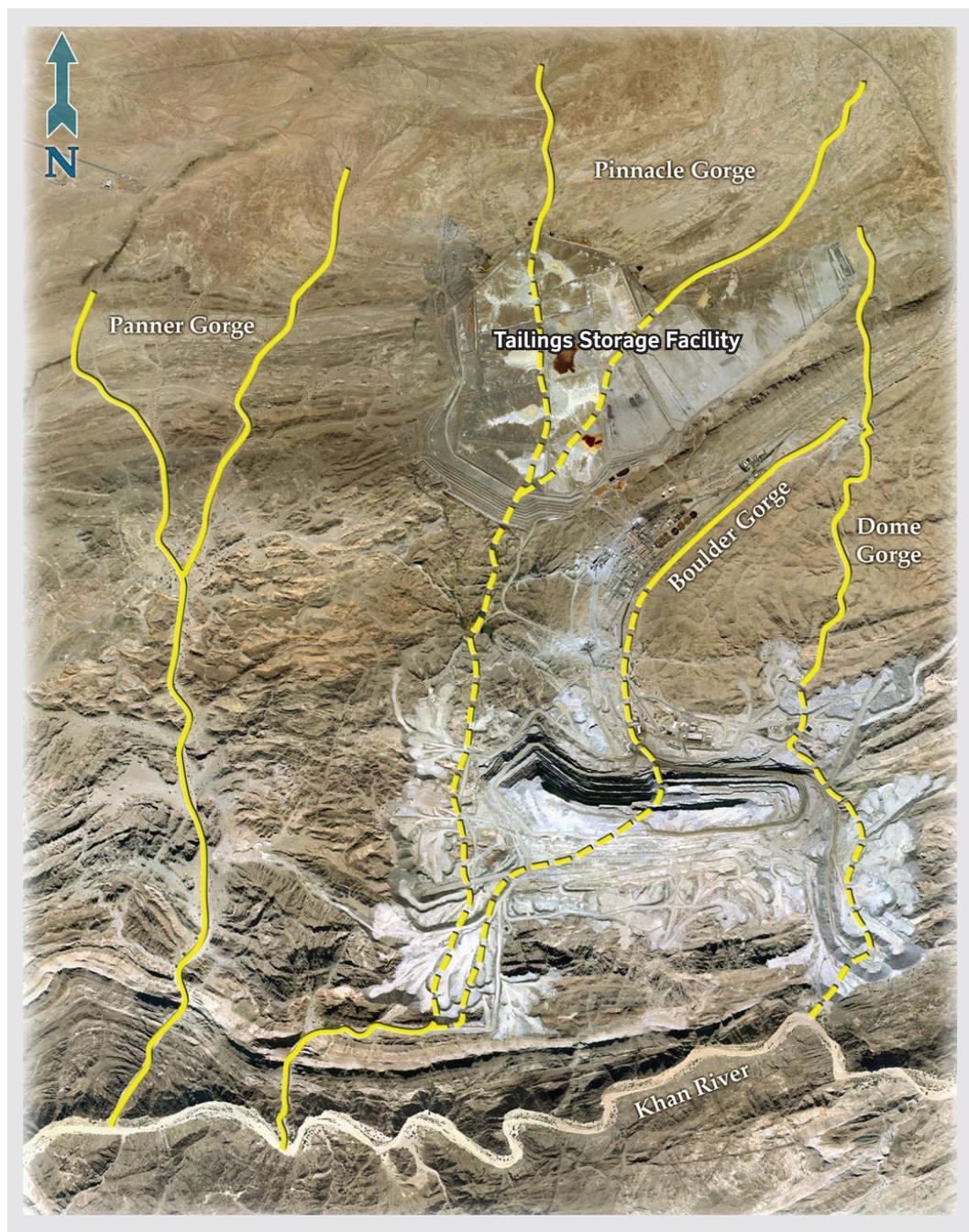
Å	–	angstrom, distance measure (1 Å = 10 ⁻¹⁰ m)
Bq	–	becquerel, disintegrations per second, unit of radioactivity
Bq/g	–	becquerels per gram, unit of specific activity
Bq/L	–	becquerels per litre
mg/L	–	milli-grams per litre, i.e. 10 ⁻³ g per litre
RMP	–	Radiation Management Plan
U-238	–	Uranium-238, uranium isotope with 92 protons and 146 neutrons
Th-234	–	Thorium-234, direct daughter of U-238
Pa-234	–	Protactinium-234, direct daughter product of the radioactive decay of Th-234
U-234	–	Uranium-234, isotope with 92 protons and 142 neutrons, direct daughter of Pa-234
TSF	–	Tailings Storage Facility

1. Introduction

Rössing Uranium Limited (Rössing Uranium) is an open pit uranium mine located in the Namib Desert, about 60 km inland from the coastal town of Swakopmund and about 10 km from the town of Arandis. The mine has a footprint of 2,300 ha, with the Tailings Storage Facility (TSF) covering an area of about 750 ha.

The TSF, whilst mostly dry on the surface, locks in considerable quantities of water. This water can seep along the underlying drainage routes into the nearby Khan River if not controlled (see Figure 1).

Figure 1: Footprint of Rössing Uranium mine, showing groundwater drainage systems into the Khan River aquifer as yellow lines. Broken lines represent historical drainage that has been cut off by mining activities.



For this reason, Rössing Uranium operates a series of de-watering boreholes and cut-off trenches, designed to re-pump and recycle any seepage water into the processing stream. In addition, a series of monitoring boreholes is used for monitoring purposes – water quality in these boreholes is measured annually in order to detect any potential seepage of contaminated water before it reaches the Khan River aquifer.

The ratio between the two uranium isotopes ¹ in the uranium decay chain is used to assess the origins of borehole water – i.e. due to natural groundwater or due to seepage from the TSF – by referring to the principle of alpha recoil, as described in Sections 2 and 3.

2. Alpha recoil explained

Natural uranium occurs in solid form, which means it is crystallised in a lattice structure. Uranium-238 undergoes a series of 14 sequential radioactive decays until a stable isotope, lead-206, is reached. This series of radioactive decays is called the uranium decay chain (see for example [1] for an overview of the uranium decay chain). The decay chains of the radioactive isotopes thorium-232 and uranium-235 are called the thorium and actinium chains respectively, but are secondary to the discussion about alpha recoil in respect to this report.

If an atom undergoes radioactive decay, its nucleus emits either an alpha or a beta particle – therefore the two types of decay are termed alpha decay and beta decay. All three naturally occurring uranium isotopes, i.e. U-238, U-234, and U-235, are alpha emitters; this means that during radioactive decay, they each emit an alpha

particle that is identical to the nucleus of a helium atom, consisting of two neutrons and two protons.

Because U-234 is a decay product of U-238, it forms at the rate that U-238 decays. Over long periods of time, equilibrium between the two isotopes is established. This condition is called secular equilibrium and means that the amount of radioactivity in a piece of rock from U-238 is exactly the same as that from U-234.

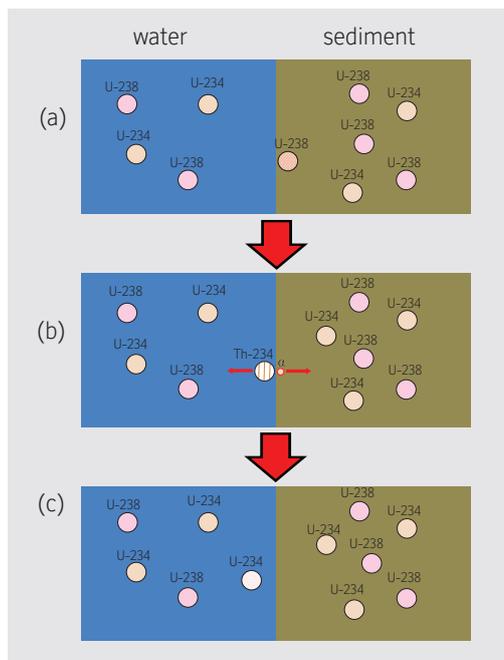
For example, 1 g of rock with a 1 per cent content of natural uranium displays a radioactivity of 124 decays per second (referred to as becquerels, Bq) from its U-238, and exactly the same activity of 124 Bq from its U-234 isotopes.

Deep within a rock (i.e. several hundred Å and more from its surface), the isotope activity ratio of U-234 to U-238 (i.e. U-234/U-238) is therefore equal to 1.

However, at the rock surface, the situation changes: As an alpha particle is ejected during alpha decay, the daughter nuclide recoils in the opposite direction and moves a distance of about 550 Å in a typical mineral (similar to a gun recoiling when a bullet is fired from it). This recoil causes a fraction of the daughter nuclides produced during alpha decay to be ejected from the host mineral and into the surrounding medium. An additional fraction of the daughter nuclides is left residing in damaged crystallographic sites within the mineral, from where they can be more readily mobilised.

Alpha recoil therefore gives daughter nuclides of alpha decay a tendency to leave their host mineral by a process that is independent of their chemistry. Alpha recoil is most important in preferentially releasing U-234 from minerals over U-238 but it also plays a role in mobilising other nuclides. Consequently, the ratio of U-234 to U-238 in natural sediments that have been exposed to water over long periods of time generally exceeds 1, and can reach values of up to 2 or more.

Figure 2: Alpha recoil explained: (a) an atom of U-238 is situated on a sediment grain surface, about to undergo radioactive decay; (b) the U-238 atom has decayed into an alpha particle and a Th-234 atom, which is ejected into the aquifer water by the recoil energy from the alpha particle; (c) the Th-234 atom has decayed into a U-234 atom, via Pa-234. (The alpha particle from the radioactive decay will end up being the nucleus of a helium atom.)



¹ Different isotopes of the same chemical element are characterised by the same number of protons, but a different number of neutrons in the atomic nucleus. For example, three isotopes of uranium (92 protons) occur naturally: U-238 (146 neutrons), U-235 (143 neutrons) and U-234 (142 neutrons).

Freshly extracted uranium, of which originates from unexposed rock in large volumes, usually contains the uranium isotopes from the uranium decay chain in secular equilibrium, i.e. at a ratio of around 1, or slightly less than 1. This allows an assessment as to the origin of borehole water: a ratio of 1 or less originates from freshly extracted uranium, whereas a ratio of U-234/U-238 exceeding 1 indicates the origin as natural sediments in contact with groundwater.

The principle is illustrated in Figure 2, which demonstrates how the 'excess' of U-234 radioactivity units relative to U-238 units can occur in aquifer water over time. When U-238 atoms decay deep inside a crystal lattice within the sediment, their decay products will remain in the crystal and hence secular equilibrium between U-238 and its daughters will remain therein.

On the sediment's surface, however, a decaying atom may obtain sufficient energy from the recoil to be

ejected from the crystal lattice, and may thus end up in the adjacent aquifer. This will not happen for all of the radionuclides in the sediment however; furthermore, the radionuclides that end up in the aquifer will preferentially be daughters of radioactive decays – there will therefore be a 'shortage' of the parent, U-238, in the aquifer. This in turn leads to the ratio of specific activities of U-234 to U-238 in the aquifer to be larger than 1. At the same time, there is a relative shortage of the decay product U-234 in the sediment, leading to an activity ratio in the sediment of U-234/U-238 equal to, or less than, 1.

This natural process takes hundreds to thousands of years to lead to a measurable dis-equilibrium but when measured, the activity ratio of U-234/U-238 in uranium bearing ores is typically between 0.8 and 1, and in the water of aquifers – which is in contact with these – it exceeds 1 and can reach values larger than 2.

3. Water monitoring and radionuclide analysis at Rössing Uranium

Uranium in natural ore is normally assumed to be in secular equilibrium, i.e. all the elements in the uranium decay chain display the same specific activity. At Rössing Uranium, this secular equilibrium is maintained as long as the ore material is a solid that is not in direct contact with the water of the surrounding Khan River aquifer. In sediments, material occurs in finer grains however, many of which are in direct contact with the surrounding aquifer's water.

In this situation, some radionuclides will be ejected into the Khan River aquifer through alpha recoil. This process, over time, leads to dis-equilibrium between the parent, U-238, and its daughters – specifically the daughter U-234 (as explained in Section 2) in the water of the Khan River aquifer.

Thus the activity ratio of U-234 to U-238 – which tends to be close to 1 (or less) in solid or freshly crushed ores, and hence also in freshly extracted uranium concentrates and their processing solution at the Rössing Uranium mine site – is likely to be of a value closer to 1.2 (or more) in the Khan River aquifer, which contains water that has been in contact with the river sediments over a long period of time.

In the Rössing Uranium monitoring boreholes, the typical sample might contain a mixture of two components:

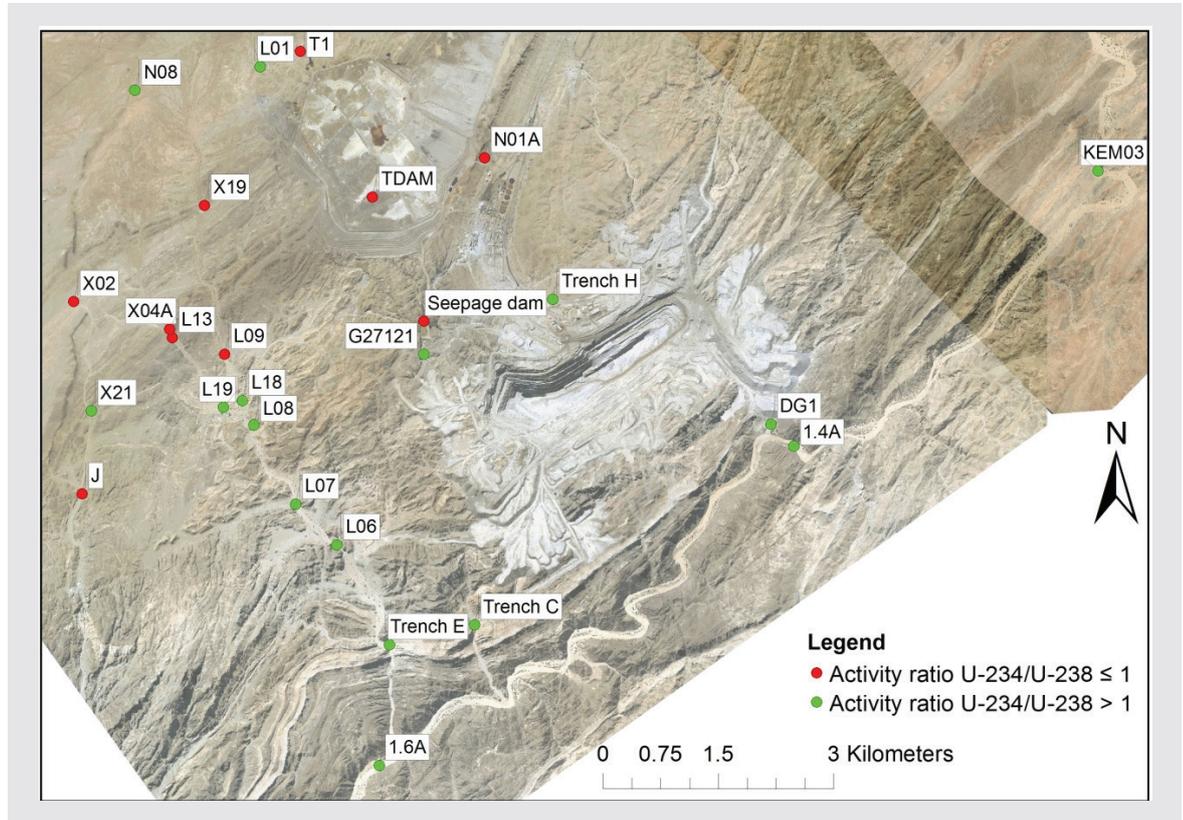
water containing some freshly extracted uranium (in secular equilibrium) that has seeped from the TSF and water containing some uranium occurring naturally in the aquifer, which is in dis-equilibrium. The activity ratio of U-234 to U-238 in these boreholes will therefore not be fixed across sampling sites; it is typically anything between about 0.9 (implying contamination with freshly extracted uranium from TSF seepage) and 2 or more (implying natural sediments in dis-equilibrium).

The water monitoring programme at Rössing Uranium comprises annual sampling of some 20 monitoring boreholes (as well as surface water from the TSF and seepage dams) and radionuclide analysis of the water samples.

Radionuclides sampled include the three uranium isotopes: U-238 and U-234 from the uranium decay chain and U-235 from the actinium chain. The activity ratio between U-234 and U-238 isotopes in the borehole water allows an assessment of the source of the water.

Radionuclide ratios are reported as part of the requirements for public exposure monitoring, as explained in the Rössing Uranium RMP [2]. The annual report to the National Radiation Protection Authority (NRPA) includes a summary of the radionuclide sampling results and its analysis (see [3] and [4]).

Figure 3: Rössing Uranium water sampling locations, January 2015. Positions are colour coded for activity ratio of uranium chain radionuclides based on 2014 monitoring results: red for sites affected by process solution; green for naturally occurring uranium.



A representative result is shown in Figure 3. Sampling locations are shown in colour on a satellite image of the Rössing Uranium mine site: red indicates a radionuclide ratio U-234/U-238 less than 1 (i.e. aquifer water mixing with process solution seeping from the TSF); green indicates a radionuclide in excess of 1, or due to naturally occurring uranium in the aquifer.

The areas immediately surrounding the TSF are seen to be affected by seepage, with process solution mixing with the natural aquifer water as a consequence. However, all the seepage trenches (trenches H, E and C in Figure 3) are unaffected by seepage from the TSF. In addition, several locations upstream of Trench E in Panner Gorge are unaffected by seepage.

There are no monitoring locations upstream of Trench C in Pinnacle Gorge as the gorge is cut off by mining operations in the SJ Pit and seepage all the way from the TSF to this trench is not possible. Trench H in Boulder Gorge, which is located upstream of the natural flow of water on its way towards the SJ Pit, is also shown to be unaffected by seepage.

From measurements done in 2014, the concentration of uranium in the sampled water was not seen to correlate with the isotope ratio. The highest uranium concentration, 67 mg/L, was found in the water on the surface of the TSF, followed by that in Trench H (7 mg/L, uncontaminated by process solution based on isotope ratio) and Borehole X19 (5 mg/L, contaminated with process solution based on isotope ratio). The lowest concentration, 0.01 mg/L, was found at borehole T1, to the north of the TSF, which is also affected by seepage water as indicated by the radionuclide ratio found there.

4. References

- [1] Von Oertzen, G. and von Oertzen, D. (2012): *Questions Answered About Uranium and Radiation*, Chamber of Mines Uranium Institute.
- [2] Rössing Uranium Limited (2014): *Radiation Management Plan*, version 2.1, August 2014.
- [3] Rössing Uranium Limited (2014): *Implementation of Radiation Management Plan, 2013 Annual Report for Rössing Uranium Limited*.
- [4] Rössing Uranium Limited (2015): *Implementation of Radiation Management Plan, 2014 Annual Report for Rössing Uranium Limited*.