Remediation of Uranium Mill Tailings Wastes in Australia : A Critical Review

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ABSTRACT: Australia has been an active participant in the global uranium mining industry since its inception in the 1940s. By the late 1950s five major mining and milling projects were operating, several small mines supplied custom ores. All of these projects were closed by the early 1960s, except for Rum Jungle which continued under government subsidy. Most sites have had lasting environmental impacts. The advances in nuclear power in the 1960s saw increasing demand for uranium and Australia again explored with remarkable success in the Northern Territory, South Australia and Western Australia. After several government inquiries in the 1970s, Ranger, Nabarlek and Olympic Dam were operating by the mid 1980s. The principal risks from uranium mill tailings wastes arise from their radioactive nature and often their chemical toxicities. A critical review of the rehabilitation of abandoned uranium mines and mill tailings as a comparison for current projects is presented.

KEYWORDS: uranium mill tailings, radon, gamma radiation, uranium mine rehabilitation

HISTORICAL OVERVIEW

Successive Australian governments have seen the mining and export of uranium as a principal way to involve itself in global nuclear affairs. The first phase of uranium mining centred around the export of uranium for the prevailing nuclear weapons programs of the British and Americans. By the late 1950s Australia had five uranium mining and milling operations, spread across the Northern Territory, Queensland and South Australia, shown in Figure 1. Several small uranium mines operated for brief periods, with the ore trucked to the nearest mill under guaranteed government pricing contracts. By the early 1960s, uranium had been proven much more abundant than originally thought, and the British and Americans stopped purchasing expensive Australian uranium. The industry freely admits that the legacy left by most of these mining and milling sites are not acceptable in modern times. Only some of these sites have been rehabilitated to date. A map of site locations is in Fig. 1.

The 1960s saw the emergence of commercial nuclear power and exploration intensified again to meet the expected demand. Several large, high grade uranium deposits were quickly discovered in the Alligator Rivers Region (ARR) in the Northern Territory, with numerous other deposits across Australia found of varying economic significance. Due to the confluence of increased environmental awareness, new federal environment legislation, the Ranger Uranium Environmental Inquiry (‘Fox Inquiry’), Aboriginal Land Rights and broad public concern on nuclear issues (centred on weapons, nuclear waste, uranium mining and the potential dangers of ionising radiation), the modern phase of uranium mining in Australia was eventually limited to Nabarlek, Ranger and Olympic Dam. Nabarlek has been closed and rehabilitated, and provides an interesting case study in assessing remedial options for a more well-managed mining operation. The author has recently completed a wide-ranging study of the impacts of old and modern uranium mines in Australia, to be published in late 2000, as a basis for assessing rehabilitation success (cf. Mudd, 2000a).

Fig. 1. Uranium Mines, Deposits & Former Nuclear Test Sites across Australia (see Mudd, 2000a)

ENVIRONMENTAL HAZARDS OF URANIUM MILL TAILINGS WASTES

The nature of uranium mill tailings wastes are unique, primarily due to their significant radioactivity. Although milling removes about 90% of the contained uranium, the decay products are retained in the tailings, comprising some 85% of the original radioactivity. The principal radionuclides of concern are thorium-230 and radium-226, with half-lives of about 75,000 and 1,600 years, respectively. Each element has different chemical properties, thus providing a complex challenge in managing the radioactive tailings in perpetuity. The decay product of Ra^{226} is radon-222, a noble gas with highly radioactive decay products. Radon and progeny all have very short lives ranging from seconds to years and is a principal radiological concern for workers and the public. The radiation from uranium series radionuclides consists of gamma, beta and alpha decay. After about one million years (~10 half-lives), the Th^{230} will have decayed to be in equilibrium with the residual uranium (depending on mill efficiency). A graph of radioactive decay over time in uranium mill tailings is shown in Fig. 2. A rehabilitated mill tailings deposit may be physically and chemically secure, however, without proper attention given to radionuclide behaviour, excessive gamma radiation and radon emanation may give rise to higher radiological exposure risks.

Uranium ore often contains elevated concentrations of heavy metals and trace elements, giving rise to the potential for chemical toxicity from surface water or groundwater contamination (Waggitt, 1994). The associated waste rock mined with the ore can therefore be a source of metals or metalloids, such as arsenic. The engineering and rehabilitation standards applied to waste rock dumps are often less than that for tailings, and thus the long term stability of waste rock dumps is less certain. By the year 2000, Australia has 9 sites containing uranium tailings, given in Table 1, with several more containing ore and/or waste rock. A review the successes and failures of remediation works to date at select sites is now presented.

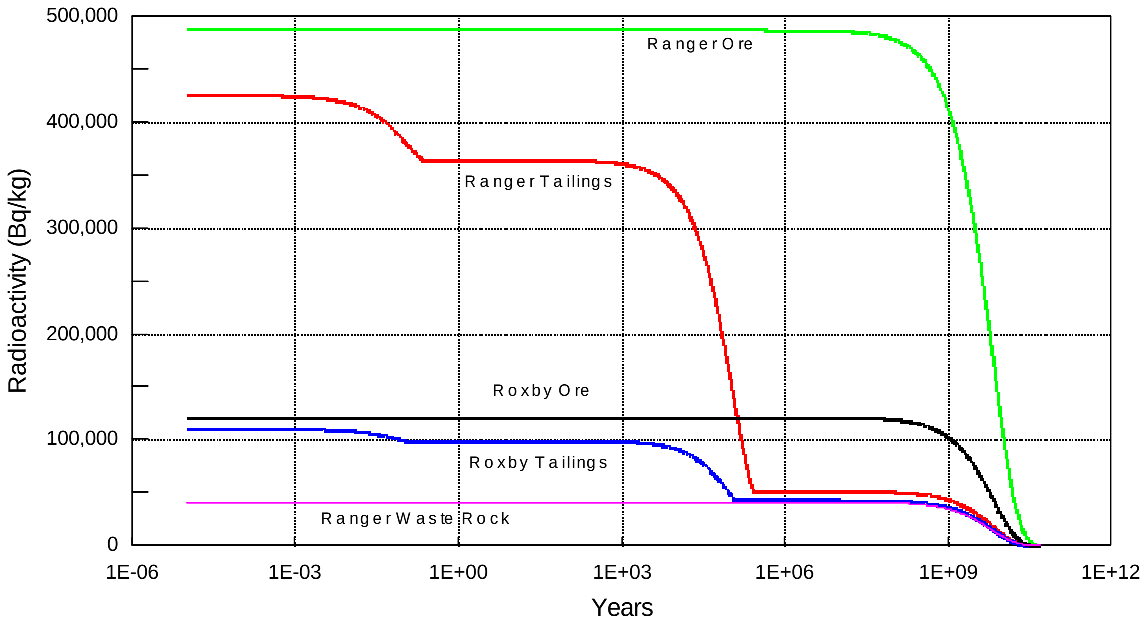

Fig. 2. Radioactive decay in tailings, ore and waste rock from the ^{238}U and ^{235}U decay series (Mudd, 2000a)

Table 1. Radioactivity of uranium tailings sites across Australia (Mudd, 2000a)

	Ranger [1]	Rockhole	Moline [2]	Nabarlek	Rum Jungle [2]
Ore Milled (t)	20,037,000	13,155	132,450	606,000	1,450,000
Ore %U_3O_8	0.324%	1.11%	0.515%	1.84%	0.321%
Mill Efficiency	89.2%	95.7%	~86	97.5%	~74%
Tailings %U_3O_8	0.035%	0.05%	~0.07%	0.048%	0.09%
Ore (Bq/kg)	490,749	1,670,955	775,413	2,769,871	483,373
Tailings (Bq/kg)	429,225	1,445,448	681,701	2,389,027	433,203
Total (Bq)	8.55×10^{15}	1.90×10^{13}	9.03×10^{13}	1.45×10^{15}	6.48×10^{14}
Tailings at 10^6 yrs (Bq/kg)	54,129	71,838	110,864	69,234	127,587

	Mary Kathleen	Radium Hill	Port Pirie	Olympic Dam [1]	Yeelirrie [5]
Ore Milled (t)	9,300,000	969,300	152,400	35,633,181	>130,000
Ore %U_3O_8	0.13%	0.13%	~0.8%	0.081%	~0.15%
Mill Efficiency	~80%	~96%	70%	64.0%	(80) ??
Tailings %U_3O_8	~0.03%	0.0054% [3]	0.24% [3]	~0.03%	0.03% ??
Ore (Bq/kg)	195,697	195,697 [4]	-	120,429	225,805
Tailings (Bq/kg)	173,923	8,129	1,204,292	109,917	200,330
Total (Bq)	1.61×10^{15}	6.67×10^{12}	1.66×10^{14}	3.91×10^{15}	2.60×10^{13}
Tailings at 10^6 yrs (Bq/kg)	41,285	8,128	366,038	43,888	45,153

[1] - data to June 30, 2000; [2] - average of all ores treated; [3] - based on residual uranium in tailings; [4] - based on ore grade as mined of 0.13%, [5] - pilot mine and mill only, figures assumed based on available data.

URANIUM MINING IN THE UPPER SOUTH ALLIGATOR VALLEY, NT

Concentrated uranium exploration in the 1950s discovered over a dozen small but rich uranium deposits in the valley of the Upper South Alligator River, just north of Katherine in the Northern Territory. Two companies were active, notably South Alligator Uranium NL, at their small Rockhole mine and mill, and United Uranium NL, who developed several mines to feed their moderate sized mill 65 km to the south at Moline. Grades ranged from 0.13% to 2.5% U_3O_8, with ore mined ranging from 500 t to 40,000 t per deposit (see Mudd, 2000a,b). The area is now part of Stage III of the Kakadu National Park World Heritage area.

At both the Rockhole and Moline mills (both using acid leaching and solvent extraction technology), the uranium tailings were discharged unneutralised onto flat areas downstream of the mills in creek lines and floodplains. There was no serious attempt to retain the tailings and observers at the time noticed that tailings were easily eroded into the river during the wet season (Waggitt, 1994). It is not accepted that this was simply the 'standard practice of the day' (due to the lack of legal requirements), since other mines around Australia disposed of tailings in engineered dams (Mary Kathleen and Radium Hill, for example). A summary of the radiation rates and heavy metals in Rockhole and Moline tailings is summarised in Table 2.

Table 2. Radiation rates and metal contaminants in the Rockhole and Moline tailings (see Mudd, 2000a)

		Rockhole			Moline		
		Average	Range	Background	Average	Range	Background
Gamma	μGy/hour	18	<2.5 to 65	~0.15	~5	<2.5 to 24	??
Radon	$Bq/m^2/sec$	~6	<5 to 21.1	??	~2	<1 to 17.9	??
	Bq/m^3	??	52 to 9,586	??	??	50 to 1,654	??
	Bq/m^3	190	- wind speed > 2 m/sec		135	- wind speed > 2 m/sec	
	Bq/m^3	1,895	- wind speed < 2 m/sec		395	- wind speed < 2 m/sec	

(mg/kg)		As	Au	Ag	Cu	Pb	Zn	Ra-226	U
M	Min.	88.8	0.026	<1	40.5	205	32	270	3.7
M	Max.	9,800	9.49	40	7,770	5,800	6,300	87,900	740
M	Ave.	1,438	1.5	12.5	661	1,227	1,107	40,290	88
M	Area	30%>500	20%>2	20%>10	20%>500	similar Zn	40%>500		similar
R	Min.	12	0.107	-	13	28	10	28,500	3
R	Max.	570	23.7	-	1,030	1,090	87	222,000	830
R	Area	30%>100	60%>2	-	1%>500	30%>500	Uniform		60%>100

M - Moline; R - Rockhole; Ra-226 in Bq/kg. 'Area' based on grid sampling surveys of tailings.

By the mid 1980s, the region was being considered for inclusion in Kakadu National Park and a series of surveys were conducted on the old mines and tailings sites to assess physical and radiological safety. The work showed that there was an unacceptable risk from both gamma radiation and radon, even for short term occupancy (Bastias, 1987). The Rockhole tailings in particular were directly adjacent to the main tourist road being used to visit Gunlom Falls. The surveys also showed that about 25% of the tailings at Moline had been eroded downstream into the catchment of the Mary River (Cull *et al.*, 1986). The gold mining boom of the mid 1980s provided the opportunity to reprocess the gold-rich Moline and Rockhole tailings, although only half of the Rockhole tailings were excavated and trucked to Moline for gold extraction and re-disposal. This saw the Moline tailings deposited in a new dam which was engineered to minimise erosion and other environmental problems.

The old adit 1 at Rockhole has been a noteable source of acid mine drainage polluting Rockhole Creek for some years, and was not addressed during the early 1990s works. The seepage waters contain uranium in solution up 650 μg/L and the aquatic impacts of the acidic waters can be observed for 500 m in the creek. Calculations show that dilution is not an appropriate regime for management of this polluted water.

With increasing visitor numbers to the Gunlom Falls area, a limited program of 'Hazard Reduction Works' was undertaken in the region in the early 1990s. This included the burial of radioactively contaminated materials in 5 shallow dump sites and the limiting of access to the old open cuts and underground shafts and adits. Annual inspections continue to highlight erosion problems and find new hot spots of radioactive contamination (Waggitt, 1996).

After Coronation Hill was blocked from proceeding by the Hawke government in 1991, a lease was signed between the Jawoyn traditional owners, Kakadu park management and the government which stated that all former mining in the region is to be rehabilitated no later than 2015. The recent discovery of Rockhole tailings again eroding into the South Alligator River (after breaching of the dump site) and the continual maintenance needed of all mine and dump sites should provide ample evidence of the urgency of completing the remediation works. The companies which exported uranium in the 1950s paid no taxes on their profits (see Mudd, 2000a) and current taxpayers are funding the cleanup - 50 years after abandonment.

RADIUM HILL & PORT PIRIE, SA

A remote, mineralogically complex and difficult mining and milling project from the outset, Radium Hill was Australia's first radium mine in the early 20^{TH} century. The SA government won export contracts in 1954 and began a new mine. The ore was pre-treated at Radium Hill using heavy media (gravity based) separation to produce a pre-concentrate about 5 times richer in uranium. The pre-concentrate was railed to Port Pirie, where a dedicated mill had been established. The refractory ore required the use of 40% acid at boiling temperatures, extracting some 70% - about the most expensive uranium produced to date.

The Radium Hill site contains 2 tailings dams with low-grade uranium ore (~0.005% U_3O_8, based on separation factors). At abandonment in 1961, the No. 2 dam had been armoured by waste rock by the last mill superintendent, compared to No. 1 dam with minimal closure work (Hill, 1986). By 1980 it was found that the No. 1 dam had weathered on the top and erosion channels had developed on the sides (Hill, 1986). On a day of strong wind, fine grained radioactive tailings were dispersed over the pastoral property (Fry & Morrison, 1982; Hill, 1986). The nearest dwelling was 15 km away. Before covering, the gamma rates averaged 0.8, ranging from 0.6 to 1.0, compared to those after covering of 0.2 and ranging from 0.1 to 0.4 (all μGy/hr) (Hill, 1986). In 1981-2, a 1 m compacted clay cover was placed over both dams and the sides were encased in a new dam wall 9 m at the base tapering to 3 m at the top (Hill, 1986). Neither dams were re-armoured on cost grounds. Other wastes on site were collected and buried in the tailings dam at this time (SSCUMM, 1997). The No. 2 dam was retained as a low-level radioactive waste repository, with no EIS or public process. Some maintenance is expected to be necessary about 20 years (Hill, 1986; Waggitt, 1994).

The Port Pirie tailings dam, consisting of six retaining ponds, was located adjacent to residential houses (~ 400 m away), inside an industrial town and on a tidal swamp in beach dunes. After abandonment in 1962, children had played in and around the tailings dam. A local boy received bad acid burns to his leg over 10 years after closure of the facility (cf. Lackey, 1983), demonstrating the persistence of the strong acidity used at Port Pirie. This was wrongly reported as 'radiation' burns but represents a significant health impact. A king tide breached the Port Pirie tailings dam wall in 1981, although details are scarce. It appeared to increase the SA government's attention, with rehabilitation works following soon thereafter. The mean annual radon emanation rate for the Port Pirie tailings, prior to rehabilitation, was estimated as 5 $Bq/m^2/sec$ (Hill, 1986). Transporting the tailings back to Radium Hill or on site burial were rejected on cost grounds. The SA government accepted an offer from the adjacent lead-zinc smelter to use reprocessed zinc slag to cover the tailings. The slag allowed a cover of 1.5 m over the tailings, reducing the radon emanation rate to 0.06 $Bq/m^2/sec$ (Hill, 1986).

Both the Radium Hill and Port Pirie sites require regular inspections and maintenance, undertaken by the SA government. These reports are not made public and thus no realistic assessment can be made of their current stability.

URANIUM-COPPER MINING AT RUM JUNGLE, NT

The first uranium mining project to facilitate Australia's active involvement in global nuclear affairs, Rum Jungle was without doubt a major industrial project for its time, especially for the Northern Territory. By 1953, the federal Bureau of Mineral Resources had proved sufficient uranium ore in 2 main deposits to warrant a commercial project, and the Australian Atomic Energy Commission (AAEC, now ANSTO), assumed ownership with site management by a CRA subsidiary, Territory Enterprises Pty Ltd (TEP). The Rum Jungle area also contained several small but significant base metal ore deposits, some of which were processed while others not (see Mudd, 2000a). A 'blind' uranium deposit was discovered at Rum Jungle Creek South in 1961 and mined to 1963. The uranium produced up until 1963 was sold to the Combined Development Agency, the UK-USA nuclear weapons procurement agency. After this time the uranium was stockpiled by the AAEC in Sydney until closure in April 1971. The various ores contained up to 3% sulfide and the mine site had become an infamous source of severe environmental pollution by the late 1960s, mainly due to acid mine drainage but also due to the large quantities of radium released into the Finniss River system (about 100 km^2 was polluted by Rum Jungle). After considerable public pressure in the 1970s, a major rehabilitation and cleanup program was initiated from 1983-86, costing $18.6 million and funded by the federal government. Neither the AAEC or CRA were held responsible for the extensive impacts from Rum Jungle.

The tailings at Rum Jungle were disposed of unneutralised to an adjacent creek line (Old Tailings Creek), combined with about 1 million litres of acidic waste waters at a pH of 1.5 (Richards *et al.*, 1996). The tailings solids settled out in the creek but proved highly erodible, although the acidic liquids drained to the East Branch of the Finniss River, 0.8 km to the west. Erosion control measures were tried but were largely ineffective, and erosion of the tailings continued up until rehabilitation at about 10 mm/year and an average annual sediment load to the Finniss River system of ~3,000 t per year. It has been estimated that the annual release of pollutants to the Finniss from the tailings was about 4.7 t of Cu, 3.5 t of Mn and 320 t of SO_4. In the 1960s tailings were disposed of in the mined out Dyson's and White's open cuts, although new water management systems failed to control the severity of the pollution cycle. Later calculations showed that the policy of dilution adopted could not have worked.

The greatest source of pollutants emanating from the Rum Jungle site was derived from the acid mine drainage from the waste rock dumps and the experimental copper heap leach pile. The main metals of concern have always been viewed by the AAEC as manganese, zinc and copper, with very little data for radium and less for uranium. Thus it is not possible to accurately assess the radiological pollution loads from Rum Jungle. A compilation of the Cu-Mn-Zn loads is given in Table 3. Rum Jungle increased the annual loads of these metals in the Finniss River system by several orders of magnitude. The higher loads and concentrations in river water led to the destruction of all flora and fauna downstream of the mine site for 10 km with significantly lower biodiversity for a further 15 km (Kraatz, 1998). Significant amounts of evaporite salts, derived from waste rock dump and groundwater discharge, still remain along the banks of the Finniss River system and contribute to the total pollution load each wet season, especially the early flows (Parker, 1999). The total amount of radium estimated to have been released by 1975 was 16.65 TBq (470 Ci; see Mudd, 2000a) and a radioactive 'anomaly' can be traced for tens of kilometres. There is continuing elevated radium levels in the Finniss River downstream of Rum Jungle, and thus claims that no radiological pollution occurred are without basis in fact and should be rejected.

The rehabilitation program of the 1980s moved the eroding tailings to Dysons open cut, reshaped and covered waste rock dumps, and treated the polluted waters in the open cuts.

Table 3. Rum Jungle Pollution Loads in the East Finniss River (see Mudd, 2000a)

Year	Flow (ML)	Rainfall (mm)	Cu (t)	Zn (t)	Mn (t)	SO_4 (t)	Ra^{226} (MBq)
1969-70	7,000	896	44	-	46	3,300	
1970-71	33,000	1,611	77	24	110	12,000	
1971-72	31,000	1,542	77	24	84	6,600	
1972-73	22,000	1,545	67	22	77	5,500	
1973-74	69,000	2,000	106	30	87	13,000	
1982-83	9,500	1,121	23	5	6	1,520	
1983-84	48,000	1,704	28	9	21	3,600	
1984-85	11,700	1,136	9.1	4.1	7.2	1,600	
1985-86	11,400	1,185	3.7	2.7	8.2	4,400	800
1986-87	13,200	1,222	5.6	2.7	8.6	2,870	800
1987-88	6,300	1,064	3.2	2.0	5.4	1,230	350
1988-89	35,000	1,600	5.4	4.4	19.2	3,940	
1989-90	3,100	900	1.8	1.6	3.9	760	
1990-91	40,500	1,590	14.9	7.4	30.5	4,000	
1991-92	7,100	1,002	3.8	2.7	9.1	1,260	
1992-93	29,900	1,421	11.9	3.9	24.7	2,696	

Importantly, the target reductions for heavy metals (70%, 70% and 56% for Cu, Zn and Mn, respectively), were not based on ecotoxicological criteria (Jeffree *et al.*, 2000) and still allowed heavy metal loads 2-3 orders of magnitude higher than those upstream in the Finniss. The multi-layered soil cover systems placed over the dumps were intended to reduce rainfall infiltration and oxygen ingress. The rehabilitation works succeeded, at least in the early years afterwards, in reducing pollution loads to the Finniss system. More recent monitoring has begun to highlight serious concerns regarding the long-term ecological stability of Rum Jungle, which demonstrate the difficulty and, in reality, the failure of the rehabilitation works.

Firstly, the infiltration rate is increasing in the waste rock dumps. The mechanism is still unclear and the use of covers is therefore still uncertain. Elevated infiltration will lead to greater pollution loads, either due to dissolution of secondary minerals or continued oxidation of primary sulfides (mechanism not determined). Secondly, AQUARISK, an ecological risk assessment program, estimates that between 5-60% of species would be affected by the continuing discharge of heavy metals and that the probability of exceeding the guideline values was close to 100% in most cases. Thirdly, vegetation dieback on the Dysons open cut cover has been increasing since 1989, due to inadequate design and construction. Fourthly, erosion problems continue to hamper rehabilitation efforts and requires constant maintenance. Finally, weeds are proving to be a major threat to the stability of the site (see Mudd, 2000a).

Assessing the success of the rehabilitation works and the continuing pollution cycle at Rum Jungle is clearly complex and appears to be exacerbated by the perceived political need to proclaim the site 'rehabilitated'. The most recent monitoring and assessments suggest that rehabilitation works have not withstood the test of time and require perpetual and proactive monitoring and maintenance. Without further works in the very near future, it appears that the pollution cycle from Rum Jungle is set to worsen for many years before it could improve.

CONCLUSIONS

The management of uranium mill tailings wastes is a complex task, requiring a sound multi-disciplinary approach. The problems include groundwater contamination, erosion, radon emanation and gamma radiation. Evidence to date from the remediation of old and modern sites, reviewed in Mudd (2000a), does not demonstrate effective long-term closure and safety.

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