Uranium mining in Australia: Environmental impact, radiation releases and rehabilitation

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Abstract. The mining and export of uranium and the impacts (and risks) of the nuclear industry have long been a contentious issue in Australia. The ongoing debate primarily relates to the established and potential dangers of ionizing radiation released to the environment from nuclear facilities, such as uranium mines or research reactors. By 2002, three uranium milling projects are operating with a further seven having been operated in the past 50 years, including numerous smaller mines. A critical aspect of the operation of a mine and/or mill is the ionizing radiation rates before, during and after a project has ceased. A number of estimates have previously been made of the environmental releases from Australian projects, such as environmental impact statements and the UNSCEAR 1993 data (although there is some controversy as to the quality of the data and assumptions used in this analysis). In order to assess the environmental impacts of ionizing radiation releases from nuclear facilities, such as radon gas or soil and water quality, it is necessary to compile and quantify these changes based on measured data from the various sites around Australia. This paper presents a brief review, based on more comprehensive studies in progress, of the changes in ionizing radiation rates, radionuclide releases and ongoing issues from some operational and former uranium projects in Australia, allowing a more accurate assessment of the measures required for protection of the environment from potentially harmful situations. The importance of detailed field radiation measurements before, during and after rehabilitation is stressed, followed by a discussion of Non-Government Organisation (NGO) views of the implications for uranium mining and milling.

1. URANIUM MINING AND MILLING IN AUSTRALIA

The history of uranium mining and milling in Australia spans the 20th century, beginning with radium mining in the early years and expanding to large scale uranium projects over the last 50 years (Figure 1).

The first uranium deposits in Australia were discovered at Radium Hill and Mt Painter in north-eastern South Australia in 1906 and 1910, respectively. Between 1906 to 1932 intermittent mining and milling occurred to extract radium with uranium as a by-product, based on mining of ~3,200 t of ore (0.2–20% U_3O_8) giving ~1.8 g of radium and up to 7 t U_3O_8 [1]. The various sites were abandoned by 1932, including the radium refineries at Hunters Hill in Sydney, NSW, and at Dry Creek in Adelaide, SA.

A new phase of uranium exploration was begun for the Manhattan Project over 1944–45 (World War II), with extensive exploration undertaken by governments, prospectors and mining companies following the war with a view to securing uranium for nuclear weapons and reactor programs. By the late 1950s, there were six uranium mills operating in the Northern Territory, South Australia and Queensland, supported by numerous smaller uranium mines. This phase ended with the closure of Rum Jungle in 1971 following the total production of ~2,500 t U_3O_8 for nuclear weapons programs of the USA and UK, 4,800 t U_3O_8 for the UK's nuclear reactor program, plus a national stockpile of ~2,100 t U_3O_8 [1]. The environmental management of these sites was generally poor or minimal.

The late 1960s saw the eventual emergence of nuclear reactors on a commercial scale and a rapid increase in the intensity of uranium exploration across Australia. The success was virtually instant and by the early 1970s new uranium provinces had been identified in the Alligator Rivers Region of the NT, central Western Australia as well as other uranium deposits of varying significance.

The 1970s coincided with increasing public knowledge and debate about the impacts of the nuclear industry, centred around nuclear weapons, reactor safety, intractable nuclear waste and the dangers of ionizing radiation. Further concerns included indigenous land rights and environmental conservation.

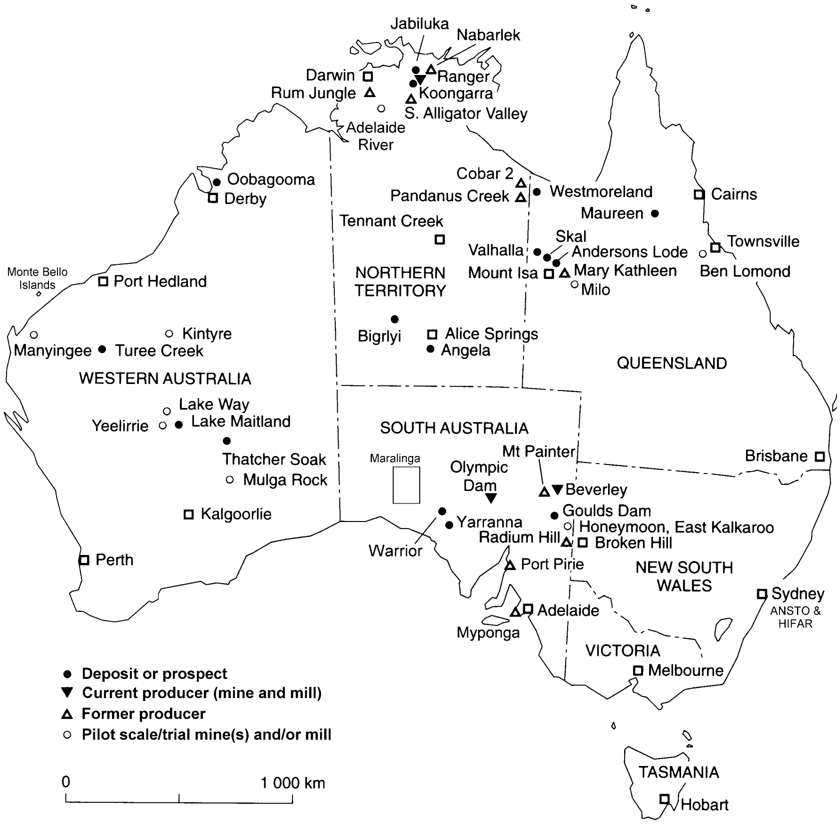

FIG. 1. Location of uranium mining and milling sites (and deposits) in Australia [1].

The Ranger Uranium Environmental Inquiry was instituted in July 1975 to investigate potential Australian involvement in the nuclear industry, principally through mining and export of Australia's uranium deposits. The inquiry presented its first report in October 1976 on the nuclear industry and its second report in May 1977 on uranium mining, land rights and national park issues in the Alligator Rivers Region [2]. The two reports essentially urged caution on all sides while arguing that the potential impacts of ionizing radiation releases from the nuclear industry, especially uranium mining, were within acceptable levels compared to background radiation. The second report also supported indigenous land rights and the creation of a large national park to be called Kakadu, with the Ranger, Jabiluka and Koongarra uranium projects deliberately excised but surrounded by Kakadu. For the Ranger project, a number of important recommendations were made with a view to minimising the environmental releases and potentially harmful impacts of radionuclides and heavy metals.

Between the adoption of most of the Ranger Inquiry recommendations in the late 1970s and the present, there have been three uranium projects at Ranger, Nabarlek (now closed) and Olympic Dam, with the Beverley acid leach mine beginning operation in late 2000. The Mary Kathleen uranium project was re-opened for six years (1976–82) plus numerous trial uranium mines and/or mills were also attempted. A thorough compilation of project data to March 2002 is given in Table 1.

There has been no comprehensive scientific analysis of radionuclide releases from uranium projects in Australia since the Ranger Inquiry. This is now more pertinent than ever, given the data now available from former, current and potential projects and the continued push for increased nuclear power in the future. This paper will present a brief analysis, based on more comprehensive studies [1, 7], of the radionuclide releases from Australian uranium projects, followed by a discussion of the implications for the long-term radiological impacts of uranium mining and rehabilitation requirements.

TABLE 1. URANIUM MINING AND MILLING DATA IN AUSTRALIA TO 31 MARCH 2002 [1]

		t Ore Milled	$\%U_3O_8$	t U_3O_8	t LGO & WR
Olympic Dam, SA	1988–	51,793,182	0.081%	27,060.2	~6,030,790
Ranger, NT	1981–	22,906,600	0.319%	65,467.6	>88,678,000
Nabarlek, NT [(M)]	1980–88	597,957	1.84%	10,955	2,330,000
Nabarlek, NT [(HL)]	1985–88	157,000	~0.05%		
Beverley, SA	2000–	ISL [†]	–	578	–
Honeymoon, SA	2003(?)–	ISL [†]	–	~ 60 [P]	–
Mary Kathleen, QLD	1976–82	6,200,000	0.10%	4,801	17,571,000
Trial Mines	1978–	various		>> 12	>> 150,000
Moline, NT	1956–64	135,444	0.46%	716.0	??
Rockhole, NT	1959–62	13,155	1.11%	139.7	??
Mary Kathleen, QLD	1958–63	2,710,483	0.156%	4,091.76	4,429,764
Radium Hill, SA	1954–61	817,000	~0.005%	852.3	??
Port Pirie, SA	1955–62	152,300 [C]	~0.8		
Rum Jungle, NT	1954–71	1,496,641	0.35%	3,530	14,283,000
Trial Mines [RJ]	1953–62	9,224.9 [RJ]	0.92%	– [RJ]	??
Radium Hill, SA	1906–31	~2,130 t	1.4% ??	<7	??
Mt Painter, SA	1910–32	~933 t	~2.1%	??	??
Total		86,980,025 t	0.168%	118,264 t	>133,472,000 t

[P] Pilot scale mining/milling; [RJ] Milled at Rum Jungle (not included in sub-totals); [†] In situ leach; [M / HL] Mill (M) or heap leach (HL); [C] Radium Hill concentrate; LGO – Low grade ore; WR – Waste rock.

2. URANIUM MINING AND MILLING AND ENVIRONMENTAL RADIOACTIVITY

A brief summary of the environmental radioactivity issues with regards to uranium mining and milling is required before analysing Australian projects. An important aspect of this is the natural or 'background' ionizing radiation that exists prior to any development works on a site.

2.1. Environmental radioactivity

Uranium consists of two principal decay chains, ^{238}U (99.3%) and ^{235}U (0.7%), each with their own radioactive decay sequence and half-lives (a minor amount of ^{234}U is in the ^{238}U chain). The various elements, such as thorium ($^{230/234}Th$), radium (^{226}Ra) and radon (^{222}Rn), have varying physical and chemical properties important in their environmental behaviour. For example, ^{230}Th is insoluble while ^{226}Ra is moderately soluble, compared to ^{222}Rn which is a noble gas. The many isotopes also decay differently through alpha or beta decay, with most isotopes releasing significant gamma radiation.

The principal radionuclide sources from uranium mining and milling are waste rock, low grade ore and tailings. The radon flux or gamma dose rate from a particular waste will be primarily determined by its uranium content (or specifically radium activity, plus moisture for radon flux). The transport of radionuclides in surface water and groundwater is an important source of environmental radioactivity and is a pivotal issue in water management at, and potential releases from, uranium mines and mills.

2.2. Background ionizing radiation

The environment has a general level of natural or 'background' ionizing radiation from the decay of U, Th or other radioactive isotopes. In Australia, background ionizing radiation is typically within global norms and primarily consists of cosmogenic and terrestrial sources (mostly gamma and some radon) [3]. The average ^{222}Rn flux from Australian soils is about 25 ± 5 $mBq/m^2/s$ [4], similar to the global average of 15 to 23 $mBq/m^2/s$ [5]. A typical gamma dose rate for Australia is about 0.02–0.1 μGy/hr [1]. The concentration of radionuclides such as uranium, radium and radon is generally low in surface waters, with subtle variation due to geological sources within a catchment area. The situtation is similar for groundwater, again related to radionuclide content in the local geological formation.

One of the principal concerns with uranium mining, excluding broader concerns about weapons, reactors and wastes, are that it could lead to increased radionuclide releases into the environment (plus the potential for accidents), altering the generally low background levels prior to mining. Whether projects are legally surrounded by World-Heritage listed Kakadu National Park or poorly managed arid lands, the environment movement opposes, on principle, any rehabilitation standards which allow permanent increases to ionizing radiation rates or radionuclide loads in the environment.

3. RADON FLUXES AND LOADS

The release of radon (^{222}Rn) gas and its decay products is a critical part of assessing ionizing radiation doses for uranium workers and the general public, though it would appear that much less is understood about the environmental behaviour of the products and their cycling through the environment. Through the mining of waste rock and ore and the creation of finely ground tailings, the physical (and chemical) nature of the dominant radon sources is considerably altered after mining compared with the geology beforehand. At some sites, it may be possible that mining and rehabilitation may indeed decrease the radon flux and load after rehabilitation while at others the data is less convincing.

The UNSCEAR 1993 report [6] uses limited operational data or optimistic company estimates of ideally rehabilitated tailings sites at the Olympic Dam, Ranger and Nabarlek projects. Their approach is based on tailings being the principal source of radon, and to a lesser the mill. This is clearly limited since waste rock, low grade ore and ^{226}Ra-contaminated areas can also be major sources. A compilation of radon fluxes and loads from uranium project sites in Australia are presented in Tables 2 and 3, with more detailed data and estimates presented for the Ranger project in Tables 4 and 5.

As can be seen from the various sites there is high variability in both the radon fluxes from different sources as well as predicted loads. For example, the predicted radon load from various configurations of Ranger tailings management have varied from <0.37 to 4,440 GBq/day [7]. Before rehabilitation, Nabarlek was predicted to have a radon flux some 10^{22} lower than pre-mining values (due to the thick layer of waste rock above the tailings), although as the data in Table 2 shows, the post-rehabilitation radon flux is less than 100 (or 10^2) times lower [1]. The UNSCEAR radon data for Nabarlek, apparently unrehabilitated, is an overestimate of actual post-rehabilitation by a factor of about two.

Another issue of importance is that of water covers for uranium mill tailings, especially at Ranger and Nabarlek. When covered by up to 2 m of water or more, the radon load derived from uranium tailings is regularly stated to be negligible, though no field data has been presented to substantiate this claim.

Based on the laboratory work of [9], the radon flux from water-covered tailings was measurably higher than due to diffusion alone, considered likely to be related to thermal and/or advective processes. After modifying radon flux equations to account for water-covered and/or variably-saturated tailings, a new model was presented to estimate radon fluxes from tailings dams, provided online by [10]. Using this model, the current radon flux and load from Ranger, for example, can be estimated as 0.75 $Bq/m^2/s$ or 73.8 GBq/day from the above ground dam (water depth of 1.3 m) and 0.08 $Bq/m^2/s$ or 3.3 GBq/day from the tailings repository in Pit #1 (water depth of >10 m) [7].

Although this analysis is brief, it demonstrates that radon fluxes and loads are highly variable and claims about a particular environmental regime need to be supported by actual field measurements. For Port Pirie, the radon flux is likely to be higher than pre-milling, even after rehabilitation of the dams, since the concentrate was imported from Radium Hill. For Nabarlek, the radon flux appears to be lower, though whether the site-wide flux and load is lower remains unclear. Waste rock dumps are evidently an important source of radon, as demonstrated by the low grade ore and waste rock dump sites at Nabarlek, Rum Jungle and Ranger (sometimes <0.02 $\%U_3O_8$). The evidence of changes in radon fluxes at different Australian uranium mine and mill sites does not allow a consistent picture to emerge, due mainly to the paucity of pre-mining and post-project field measurements. The inadequacy of the UNSCEAR approach, which assumes tailings as the primary source of radon, is limited and needs to be expanded to include other sources such as waste rock and contaminated areas.

TABLE 2. RADON FLUXES AND LOADS FROM SELECT URANIUM MINING AND MILLING SITES IN AUSTRALIA [1, 7]

	Waste Type ‡	Area (ha)	Uranium (%U_3O_8)	^{222}Rn Flux (Bq/m^2/s)	^{222}Rn Load (GBq/day)
Rum Jungle, NT	T	35	~0.086%	~2.9	88
White's (Rum Jungle), NT	WR	26.4	0.01%	1.1	25
Rum Jungle Creek South, NT	WR	21.9	0.054%	2.7	51
Rum Jungle, NT	R $^{(P)}$	~500	–	0.14	–
Rockhole, NT (average)	T	~2	0.048%	<5–21.1 (~6)	10.4
Moline, NT (average)	T	~18	0.066%	<1–17.9 (~2)	31
Port Pirie, SA	T	~30	~0.24%	5	130
Port Pirie, SA	R $^{(D)}$			0.12	3
Jabiluka, NT (Mine Valley)	PM	–	–	0.046	–
Jabiluka, NT (Proposed Haul Road)	PM	–	–	0.025	–
Nabarlek, NT	PM	~5	–	3.7–44.0	–
Nabarlek, NT	R $^{(D)}$		–	1.03 ± 0.80	4.5
Nabarlek, NT	U-T		–	2.1	9.1
Ranger, NT	PM	245	–	1.78	377
Ranger, NT	U-T	–	–	0.9 ^{AE} / 0.1 ^{AQ}	–
Ranger, NT	R $^{(P)}$	–	–	'0'	'0'
Koongarra 1, NT (Koongarra 2)	PM	12.53	–	2.43 (<0.05)	26.3
Olympic Dam, SA	PM	–	–	0.025	–
Olympic Dam, SA	Mill & T	~400	–	–	260–290
Olympic Dam, SA	U-T	75	–	1.6	103.7
Olympic Dam, SA	U-T $^{(P)}$	720	–	0.2	124.4
Honeymoon, SA	PM	–	–	0.035	–

‡ U-T – UNSCEAR 1993 assumed tailings (T) data, ^{AE} – sub-aerial, ^{AQ} – sub-aqueous; WR – waste rock; PM – pre-mine (generally above ore zones); R – rehabilitated site (proposed $^{(P)}$ or done $^{(D)}$).

TABLE 3. MEASURED RADON FLUX PROPERTIES AT RANGER AND NABARLEK [7]

Mine/Mill Site Ore / Tailings	%U_3O_8	^{226}Ra Bq/kg	^{222}Rn Flux Bq/m^2/s
Ranger waste rock (dry / wet)	–	–	1.2 § / 0.47
Ranger waste rock	–	–	0.52
Ranger very low grade ore	0.03%	3,112	1.3
Ranger tailings (dry)	0.033%	22,100	10.4
Ranger tailings dam wall	0.012%	1,245	0.21
Nabarlek tailings	0.034%	190,853	4.710
Nabarlek waste rock	0.013%	1,348	0.26

§ Calculated based on a measured radon-in-air concentration profile.

TABLE 4. PRE-MINING CALCULATED RADON FLUXES AND LOADS FROM THE RANGER ORE ZONES [8]

Region	Radon Flux	Area	Radon Load
Orebody #1	4.1 Bq/m^2/s	44 ha	155.8 GBq/day
South of #1	1.0 Bq/m^2/s	27 ha	23.3 GBq/day
Orebody #3	2.5 Bq/m^2/s	66 ha	142.6 GBq/day
North of #3	1.0 Bq/m^2/s	27 ha	23.3 GBq/day
Strip #1–#3	1.0 Bq/m^2/s	27 ha	23.3 GBq/day
East of Strip	0.13 Bq/m^2/s	27 ha †	3.0 GBq/day
West of Strip	0.23 Bq/m^2/s	27 ha †	5.4 GBq/day
Total	1.78 Bq/m^2/s	245 ha	376.7 GBq/day

† No area given, value assumed.

TABLE 5. PROGRESSIVE ESTIMATES (GBQ/DAY) OF COMBINED RADON LOADS FROM THE RANGER PROJECT [7]

Year	T. Dam Type	Plant	Ore Stockpiles	Waste Rock	Pits	Tailings	Total
Pre-mine		0	0	0	371.8	~4.92 ‡	376.7
1975 (2)	>2 m WC *	44.0	19.2 §	–	32.2	<0.37	95.5
1977 (3)		20.0–148.0	~96.2 §	–	20.0–281.2	1.44–14.4	137.6–539.8
1981	Dry	–	–	–	–	3,990	–
1980's	sub-aq. †	–	–	–	–	196.8	–
1992	sub-aerial	146.9	318.0	7.6 (4)	43.9	96.2	612.6
1993	sub-aerial	149.5	324.9	15.1	25.9	94.2	609.5
1990's	mixed WC *	–	–	–	–	77.1	–

‡ Assuming a pre-dam flux of 0.05 $Bq/m^2/s$. § Includes waste rock. † Sub-aqueous. * water cover.

4. GAMMA RADIATION

An important aspect of uranium project rehabilitation is residual gamma radiation dose rates. Some uranium deposits have been discovered in Australia by searching for small, localised areas of gamma radiation which indicate potential uranium mineralization (eg. Ranger, Yeelirrie, etc). On the other hand, many uranium deposits lie buried beneath a sedimentary cover or other geological formation and there is no elevated gamma dose rate to signify the presence of uranium. There is some pre-project data available for select uranium sites on gamma dose rates (or simply 'counts per second', cps), compiled in Table 6, though it is not as comprehensive as desired.

The data shows that for most uranium deposits in the Alligator Rivers Region, there is no significant or elevated gamma radiation dose rate noticeable, although some sites have small and localised areas (with Ranger being an obvious, rare exception to this). For many Australian uranium deposits a similar table could be demonstrated (eg. Olympic Dam, Beverley, Manyingee) with some deposits showing geologically localised areas of elevated gamma dose rates (eg. Yeelirrie, Kintyre, Mt Painter).

TABLE 6. BACKGROUND RADIATION COUNTS AT SELECT URANIUM SITES WITHIN THE ALLIGATOR RIVERS REGION [7]

	Aerial Radiometric Surveys				Ground Surveys	
Uranium Deposit	Total Count (cps)	x Back-ground ‡	No. § Lines	Area	x Back-ground ‡	Area
Koongarra	345	~6	1	100 m	10	90×90 m
Ranger 1 & 3	1,460–>4,000	~30–>80	4	6.5x1.5 km	30–250	6×0.5 km
Ranger 9 / 68	–	1	None	–	1 / (radon) †	–
Jabiluka 1	–	1	None	–	2	105×45 m
Jabiluka 1					1.5	80×40 m
Jabiluka 2	–	1	None	–	1	–
Nabarlek	700–1,960	~20–65	2	0.5x1.8 km	50	0.15×1.5 km
Coronation Hill	–	–	–	–	2–3	0.4 ha
El Sherana	–	–	–	–	1.5–10	2 ha

‡ Ratio of anomaly to background count (~20–100 cps; exact figure used is often not quoted, which will depend on the survey height, equipment used, etc). § Number of flight lines. † 'Radon' anomaly.

The process of uranium mining and milling leads to the dispersal and changed nature of many radionuclide sources, thus posing a particular challenge for rehabilitation. Some examples include [1]:

(1) Nabarlek – mineral exploration and environmental surveys were used to estimate an average pre-mine gamma dose rate of about 0.18 μGy/hr [11]. Detailed post-rehabilitation surveys have been undertaken, based on correlation of aerial and ground radiometric surveys by [11], with the average gamma dose rate being derived at 0.27 μGy/hr [11]. The gamma dose rate above the former ore zone has been decreased by about half, however, over the 97.6 ha of the project area the gamma dose rate has therefore been increased by 50%.

(2) Rum Jungle – a 'radioactive anomaly' can be traced downstream in the Finniss River for many kilometres. There is no published aerial or ground gamma surveys for Rum Jungle, especially after rehabilitation, and based on geology and site operations, it is highly likely that an increase similar to or perhaps higher than Nabarlek has also occurred, but over a much larger area.

(3) Hunter's Hill (Sydney, NSW) – the site of the radium refinery for Radium Hill ore between 1911–15. In the late 1970's it was discovered to contain high gamma dose rates (as well as radon) ranging from 0.14 to 1.4 μGy/hr, derived from the 3,000 t of radium mill tailings [1, 12].

(4) Rockhole (South Alligator Valley, NT) – the poor management of uranium mill tailings (as well as partially effective recent 'hazard reduction' works) has seen the surrounding areas reach gamma dose rates ranging from 0.33 to 6.0 μGy/hr through further erosion and dispersal.

(5) Moline (near the South Alligator Valley, NT) – due to the erosion and dispersal of about 63,000 t of mixed uranium-base metal tailings, gamma dose rates 1 km downstream were around 0.25 to 1.0 μGy/hr, higher than the measured background of about 0.02 μGy/hr.

Although many of the gamma dose rate examples quoted do not represent acute or dangerous situations, from an environmental perspective these 'chronic' and perhaps permanent increases are of legitimate concern. Changes in gamma dose rates clearly need to be given greater consideration in the long-term assessment of ionizing radiation and radionuclide loads released by uranium projects.

5. ER QUALITY

The management of water and associated (or potential) impacts is often the most publicised aspect of radionuclide releases from uranium facilities in Australia. Historically, this is related to the serious water quality and environmental impacts from Rum Jungle, concerns over mining and national parks (eg. Ranger), seepage from tailings management facilities (eg. Olympic Dam) as well as impacts on groundwater from in situ leach mines (eg. Beverley, Honeymoon). A summary of the radionuclide issues from these various sites and their associated environmental issues is presented.

5.1. Surface water

The Ranger Inquiry [2] made strong recommendations that uranium projects in the Alligator Rivers Region operate a 'no-release' water management system. Initially the Jabiluka, Koongarra and Nabarlek projects accepted this approach, though Ranger fought to maintain the legal right to release contaminated minesite waters under certain intense wet season conditions (eg. Magela Creek flow >20 m^3/s). The attention which the Ranger Inquiry placed on water was a combination of national park and indigenous concerns and the lasting impacts from Rum Jungle, where poor waste management and acid mine drainage had led to widespread contamination of the Finniss River for some 100 km^2 [1].

The NGO movement continues to oppose the discharge of radionuclides to surface water ecosystems, and, in general, believes all wastes from mining should be safely contained within a project area.

5.1.1. Rum Jungle

A detailed study and analysis of the impacts from Rum Jungle is given in [1], with a concise summary in [13]. The principal points concerning environmental radionuclides are:

— The discharge of 1 ML/day of acidic liquid wastes and gradual erosion of tailings deposited on lowlands adjacent and into creeks which flowed into the Finniss River led to some 17 TBq of radium (^{226}Ra) entering the environment. Accounting for the radium has been extremely poor, with very little focus on radium uptake in the environment or current levels leaching from the site. Monitoring of radium activities in the Finniss River was stopped in 1988, shortly after rehabilitation, with annual loads still being of the order of 0.4 to 1.6 GBq per wet season.

— Despite uranium being highly soluble in the acidic, oxidising geochemical environments prevailing within wastes at Rum Jungle, there was no U concentrations or load data published in studies in the 1970's, with the only data available being for the 1992/93 wet season (Table 7).

5.1.2. Alligator Rivers Region

The confluence of Aboriginal land rights, uranium mining and environmental conservation have always made scientific debate about Ranger and nearby projects highly contentious, with water (and tailings) management often at the top of the list of concerns. This section is based on [1, 7, 14].

After considerable debate, the Ranger uranium mine was forced to accept a 'no-release' water management system by the mid-1980's. However, poor data and understanding of evaporation and rainfall in the region led to the accumulation of contaminated waters at Ranger and Nabarlek [1].

To overcome this, the typical approach has been to temporarily remove contaminants from water through irrigation onto nearby pristine lands, or more recently, the use of artificial wetlands. The principal mechanisms suggested to remove radionuclides (U, ^{226}Ra) from the water include adsorption on soils and plant uptake. The less reactive contaminants (eg. Mg, NH_4, SO_4) are often left to reach groundwater and adjacent creeks. This clear divergence from 'no-release' at Ranger, Nabarlek and again at Jabiluka is of significant legitimate concern to the environment movement, especially as long-term sink and uptake issues are poorly addressed in ongoing project management and regulation.

Throughout its operation, the Ranger project has had to meet specific downstream water quality in the Magela Creek (at gauging station 'GS8210009'), near the boundary with Kakadu National Park. The debate again flared in early 1995 when Ranger applied to discharge contaminated 'Restricted Release Zone' (RRZ) water to the Magela, and, although winning the court case against the traditional owners (who were clearly opposed), Ranger withdrew the application.

In recent years a new system has been implemented to assess the impacts on water quality downstream of Ranger, with a similar regime also in place for the stalled Jabiluka project. The system is based on the use of three trigger levels to assess water quality, rather than specific concentrations and loads. The triggers are termed 'focus', 'action' and 'limit', with focus suggesting that heightened vigilence over environmental data is necessary, action requires investigation and limit suggests a failure of management systems onsite (that is, potentially unacceptable environmental impacts). The levels are derived using methodology in the revised Australian Water Quality Guidelines [15]. In general, the aim is to prevent water quality deviating significantly from background (or upstream) by deriving the trigger values based on statistical variation or using ecotoxicological data. The criteria for Ranger and Jabiluka are summarised in Table 8, including typical background values.

In general, there is a strong trend of increased Mg-SO_4 concentrations in the Magela Creek due to Ranger, though the data for metals and radionuclides is less consistent. Some of the principal concerns (among many) relate to the high U concentrations allowed (5.8 μg/L) over background, especially for Jabiluka with a background of <0.01 μg/L, the creep of operations into previously pristine areas (eg. RP1), the high concentrations of leaks or failures, and the continual focus solely on Kakadu while downplaying the potential environmental impacts within the Ranger and Jabiluka project areas.

TABLE 7. FINNISS RIVER WATER QUALITY, DOWNSTREAM OF RUM JUNGLE, 1992/93 WET SEASON (μG/L) [13]

(† mg/L)	Al †	Ca †	Fe †	As	Ba	Co	Cr	Cu	Ni	Pb	Th	U
Average	3.6	9.9	1.71	4.1	37	176	5	485	169	76	3.3	33
Minimum	0.21	4.2	0.096	0.6	21	53	0.7	180	53	2	0.02	6
Maximum	9	29	14	41	120	480	33	1,100	430	880	26	63

TABLE 8. ANNUAL DOWNSTREAM WATER QUALITY SUMMARY FOR RANGER AND JABILUKA [1, 7, 14, 16, 17, 19]

			pH ‡ –	EC ‡ µS/cm	Mg ‡ mg/L	SO_4 ‡ mg/L	NO_3 mg/L	Mn µg/L	^{226}Ra mBq/L	U µg/L
1979–01	Ranger	Crit. †	ND	ND	10	19	0.6	24	13 §	3.8
2001–	Ranger	Focus	5.84–6.50	22	(use	(use	ND	11	>10	0.30
Present		Action	5.51–6.83	30	EC)	EC)		19	>10 [1]	1.90
		Limit	5.18–7.16	43				37	>10 [2]	5.8
2000/01	MC-U	Ave-	5.93	10	0.48	0.28	ND	4.96	ND	<0.1
Wet	MC-D	rage	6.02	12	0.72	0.73		4.35	3–20	0.1
2001–	Jabi-	Focus	4.61–5.31	15	0.37	0.60	0.30	ND	ND	0.02
Present	luka	Action	4.27–5.65	18	0.50	0.91	0.63			0.03
		Limit	3.92–6.00	21	0.76	1.50	1.26			5.8
2000/01	SC-U	Ave-	4.70	9	0.30	0.60	0.15	4.11	3–9	0.014
Wet	SC-D	rage	4.98	12	0.25	<0.1	0.07	2.43	<3–16	0.022

§ GBq/yr. 1/2 >10 mBq/L above upstream for 90 consecutive days / annual average. ‡ Guideline only. MC / SC – Magela / Swift Creek; U/D – Up- / Downstream; ND – No data. † Load limits also applied.

5.2. Groundwater

The protection of groundwater is widely recognised as a fundamental environmental issue, especially for the 21ST century. The experience in Australia, however, suggests that the attention by regulators and companies is clearly not in step with community expectations [1, 7, 13, 14, 18]. Some of the many complex issues include the long-term impacts on groundwater quality (eg. redox state, metals), potential for contaminant migration through fractures (or other permeable pathways such as carbonate units) and potential hydraulic connections between groundwater and surface water ecosystems.

6. DISCUSSION AND CONCLUSIONS

This paper has presented a concise analysis, based on more comprehensive studies in progress (which governments have failed to undertake properly), of the impacts of the uranium industry in Australia, thereby illustrating particular issues around ionizing radition and the protection of the environment. There are many important issues raised by the work which the environment movement sees as pivotal.

It is clear that the release of radionuclides into the environment or changes in ionizing radiation rates are still poorly quantified from uranium mining and milling, despite some improvements in recent years. Critical issues such as radon flux and loads, gamma dose rates and impacts on groundwater need to be more rigorously monitored and assessed. While surface water and tailings receive most of the attention, the downstream water quality standards in the NT allow for substantive increases in uranium. For example, at Jabiluka, the 'limit' value is some 580 times higher than background. It is not merely an academic exercise – even approaching a quarter of 5.8 µg/L shows that significant environmental impact (not just change) has or is occurring due to the increase over background. This issue remains of deep concern to Aboriginal people and the environment movement.

There are many complex issues which fail to be taken into proper account when examining questions of ecotoxicology and the potential impacts of ionizing radiation and radionuclides in the environment:

- the ultimate capacity of sinks, such as wetlands, soils and plants, to retain limited quantities of contaminants such as U, Mn, ^{226}Ra, etc;
- the cycling of radionuclides through the environment, between soils, plants, insects, aquatic species, mammals, etc (ie. both macro and micro scales);
- the radionuclide transfer factors (or bioaccumulation factors) between these components of the environment in different climates (eg. ^{226}Ra uptake is higher in the tropics than arid lands);
- the inability to focus on 'low-dose, long-term' exposure to radionuclides which cause chronic, sub-lethal effects, non-fatal diseases, chemical toxicity and/or genetic damage (as opposed to the traditional approach of 'fatalities' in most current ecotoxicological testing regimes);

— the lack of a truly long-term approach to assessing and regulating uranium operations;

— the rehabilitation standards to try and minimise the long-term release rates; etc.

The available evidence from uranium project sites around Australia shows that, in general, ionizing radiation rates and radionuclide are generally within normal background prior to development. At many of these sites, the operations appear to have led to deterioration from the pre-project situation. The increased radiation rates are also cumulative in their impacts over all project sites. Rehabilitation is proving more difficult than predicted. It is well documented that radionuclide uptake and internal exposure to ionizing radiation is dangerous. The absence of being able to prove harm at low doses should not be a weak regulator's excuse to allow radionuclide releases into the environment. The 'As Low As Reasonably Achievable' (ALARA) principle, which has to take into account social and economic issues, is often used to justify the low dose exposure of people and the environment without reasoned and informed debate. There is a general understanding that people are the most sensitive to ionizing radiation and if they are protected, the environment should be also. To separate people from the environment is clearly irrational (eg. the Ranger Inquiry included people in 'environment') and against the global push for sustainability, of which the Precautionary Principle is a key standard adopted by many governments and communities in their ongoing journey in this regard. The onus of proof should be on industry and government to demonstrate that there are no impacts on the environment from ionizing radiation and radionuclides. Until there is a broader concensus (from all), it is perhaps more appropriate to follow the ALATA or 'As Low As Technically Achievable' principle. Given the future potential for expansion of the nuclear industry (eg. uranium mining), it is imperative that the sources and environmental impacts of ionizing radiation are better quantified and understood.

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REFERENCES

[1] MUDD, G.M., Uranium Mining and Milling Wastes in Australia: Past, Present and Future Management, Research Report (Nearing Completion), Melbourne, Australia (2002) ~150.

[2] FOX, R.W., et al., Ranger Uranium Environmental Inquiry, First Report October 1976, Second Report May 1977, AGPS (1977).

[3] WEBB, D.V., et al., Background Radiation Levels and Medical Exposures in Australia, Rad. Prot. Aust. **16** 2 (1999) 25–32.

[4] SCHERY, S.D., et al., The Flux of Radon and Thoron From Australian Soils, J Geophy. Res. **94** (D4), (1989) 8567–8576.

[5] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Ionizing Radiation: Sources and Biological Effects., UNSCEAR Report to the United Nations General Assembly, UN Publication E, 82, IX, 8-06300P (1982).

[6] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Sources and Effects of Ionizing Radiation, UNSCEAR Report to the United Nations General Assembly (1993).

[7] MUDD, G.M., Ranger Uranium Mine: Continuing Grounds for Concern, Research Report (In Preparation), Melbourne, Australia (2002) ~350.

[8] KVASNICKA, J., et al., Assessment of Background Radiation Exposure at Ranger Uranium Mine, Rad. Prot. Aust. **12** 4 (1994) 65–70.

[9] NIELSON, K.K., et al., Surface Water Hydrology Considerations in Predicting Radon Releases From Water-Covered Areas of Uranium Tailings Ponds, Proc "Geotechnical & Geohydrological Aspects of Waste Management", Fort Collins, CO, USA (1986) 215–222.

[10] WISE Uranium Project, Uranium Mill Tailings Radon Flux Calculator. Researched by Peter Diehl, Germany (2002) (www.antenna.nl/wise/uranium/)
[11] MARTIN, P.C., Radiological Impact Assessment of Uranium Mining and Milling, PhD Thesis, Queensland Uni. of Technology, Brisbane, QLD, February (2000) 226.
[12] GANDY, G.F., Radium Contamination of Residential Areas, Proc. "2ND Annual Conference of the Australian Radiation Protection Society" (1977) (ARPS Bulletin 2/82, 117–129).
[13] MUDD, G.M., Uranium Mill Tailings in the Pine Creek Geosyncline, Northern Australia: Past, Present and Future Hydrogeological Impacts, Proc. "Uranium Mining & Hydrogeology III", (Submitted), Freiberg, Germany, September (2002).
[14] MUDD, G.M., Review of Water Management at Jabiluka: Environmental Issues and Recommendations, Gundjehmi Aboriginal Corporation, December (2001) 31 (www.mirrar.net)
[15] ANZECC, et al., Australian and New Zealand Guidelines for Fresh and Marine Water Quality, National Water Quality Management Strategy, ANZECC & ARMCANZ, Paper No. 4, October (2000) (www.ea.gov.au/water/quality/nwqms/)
[16] OFFICE OF THE SUPERVISING SCIENTIST, 2000–2001 OSS Annual Report, (www.ea.gov.au/ssd/)
[17] NORTHERN TERRITORY SUPERVISING AUTHORITIES, Environmental Surveillance Monitoring in the Alligator Rivers Region, NTSA Six Monthly Reports, No's 39–42, Darwin, NT.
[18] MUDD, G.M., Critical Review of Acidic In-Situ Leach Uranium Mining: 1 USA and Australia / 2 Soviet Block and Asia, Env. Geology **41** (2001) 390–403/404–416.
[19] LEGRAS, C., et al., Chemical Characteristics of Stream Waters in the Jabiluka Region, Supervising Scientist Research Summary 1995–2000 [DRAFT] (2002) 71–77.

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