An Environmental History of Uranium Mining in Australia : A Scientific Review

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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 civilian (and military) nuclear facilities, such as uranium mines or research reactors. In Australia the debate is principally around uranium mining due to our numerous known deposits. By 2005, three uranium projects are operating with a further seven having been operated in the past 51 years, including numerous smaller mines and an earlier phase of attempted radium mining. The first major phase of production was for both military and civilian nuclear programmes, and left a legacy of environmental problems of varying scale (some major). The total production was small but allowed Australia an entry in the global industry. In the 1970's major new discoveries placed Australia in the dilemma of whether or not to mine uranium on a large scale. The public debate was fierce – from all sides. This generation of mines are still operating today, and have been operated in an improved fashion over the 1950's era approach. There is now a broad base of field and operational data available to analyse and assess the environmental impacts of uranium mining – from historic mines as well as currently operating mines. This data can be used to establish potential rehabilitation criteria, assess the extent of contamination due to operations (water, soils, radiation, etc), contribute to global studies of radiation releases/estimates from the nuclear industry (eg. UNSCEAR), or even to develop regulatory standards. This paper will present a brief overview of the history of uranium mining in Australia, followed by an analysis of the data currently publicly available on most projects, concluding with a general discussion of the challenges facing the current phase of the uranium debate. Overall, it provides a unique insight into the measured environmental impacts of uranium mining (to date), and allows a rational basis for many of the vexed issues to be further debated in the public arena.

1. A Brief History of 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 51 years (Fig. 1). Although the history is significant, there has very little compilation and critique of the scientific data on the environmental aspects of uranium mining, especially the data which has become available more recently. This paper compiles and analyses this data set from an environmental perspective.

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, mining some 3,200 t of ore (grading 0.2-20% U_3O_8) to give ~1.8 g of radium and up to 7 t U_3O_8. The projects were abandoned by 1932, including a radium refinery at Hunters Hill in Sydney, NSW (aka 'Woolwich'), and at Dry Creek in Adelaide, SA. There still remains a small radioactive waste legacy at the Hunters Hill/Woolwich site, presenting a difficult urban radioactive waste dilemma [Mudd, 2005a].

A new phase of uranium exploration was begun alongside 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 [Mudd, 2005a]. 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. The environmental management of these sites was generally poor or minimal, with Rum Jungle leaving a particularly damaging environmental legacy [Mudd, 2005b].

The late 1960s saw the eventual emergence of nuclear reactors on a large 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 deposits of mostly minor significance.

The 1970's 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. Curiously, many of these issues were raised as early as the 1940's by Melbourne scientist John Earl Bowker, including the assertion that reactors were covers for bomb factories [Bowker, 1948].

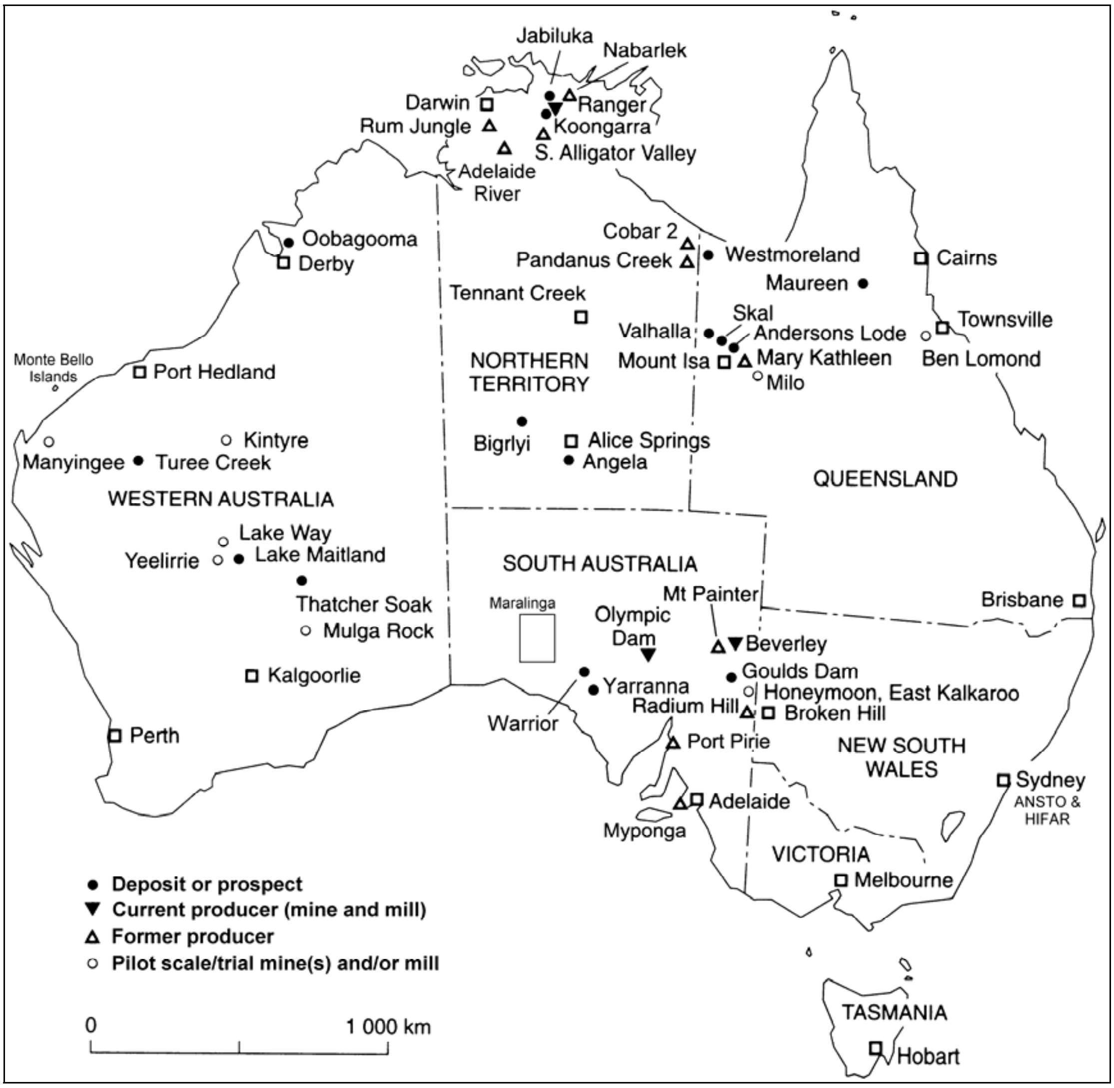

Figure 1 : Location of uranium mining and milling sites (and deposits) in Australia [Mudd, 2005c]

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 uranium. 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 [Fox *et al.*, 1976 & 1977]. 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 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 four uranium projects at Ranger (1981-), Nabarlek (now closed, 1980-88), Olympic Dam (1988-) and Beverley (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 June 2005 is given in Table 1.

There has been no comprehensive independent scientific analysis of the environmental impacts from uranium projects in Australia since the Ranger Inquiry. This is now more critical than ever, given that there is now much more extensive data available from former, current and potential projects and the continued push for nuclear power. This paper will present summarise the various analyses undertaken to date as well more comprehensive studies still in various stages of completion [eg. Mudd, 2005b, d]. The principal aspects to be addressed are the volumes of uranium mine wastes produced to date (and associated statistics), environmental radioactivity and changes due to uranium mining, radon fluxes and loads, gamma radiation, water quality impacts (surface waters and groundwaters), milling issues, economic uranium resources, and finally rehabilitation. The paper will conclude with a discussion of the environmental implications for the current uranium-nuclear debate.

Table 1 : Uranium mining and milling data in Australia to 30 June 2005 [Mudd, 2005b]

		t Ore Milled	**%U_3O_8**	**t U_3O_8**	**t LGO & WR**
Olympic Dam, SA	1988-	79,095,326 [§]	0.075% [§]	39,101 [§]	~9,750,000 [§]
Ranger, NT	1981-	29,609,000	0.31%	81,925	»105,500,000
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-	~24,000 ML [ISL †]	~0.18 [ISL †]	3,612	-
Honeymoon, SA [P]	1998-2000	897 ML [ISL, P †]	~0.12 [ISL †]	29.4 [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		**120,950,653 t**	**0.149%**	**149,775 t**	**>158,500,000 t**

[§] ***Missing April-May 2005 due to the takeover of WMC by BHP Billiton***; [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. Two important aspects include 'background' ionizing radiation and the contribution of uranium mining to normalised global radiation doses.

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) [Webb *et al.*, 1999]. The average ^{222}Rn flux from Australian soils is about 25 ± 5 mBq/m^2/s [Schery *et al.*, 1989], similar to the global average of 15 to 23 mBq/m^2/s [UNSCEAR, 1982]. A typical gamma dose rate for Australia is about 0.02-0.1 μGy/hr [Mudd, 2005b]. 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.

2.3. *Contribution of Uranium Mining to the Global Nuclear Industry Radiation Dose*

In recent years there has been various attempts at quantifying the global radiation doses released from the nuclear chain normalised per energy generated (eg. *person.Sv/GWe.yr*). The primary work in this regard is that of the United Nations Scientific Committee on the Effects of Atomic Radiation ('UNSCEAR') [UNSCEAR, 1993, 2000], as well as its critiques [eg. Chambers *et al.*, 1998a, b; Frost, 2000]. For uranium mining, the UNSCEAR approach is to assume that all radiation doses are derived from the release of radon gas from tailings only. These analyses form the bases upon which comparative life cycle assessments of energy production can be undertaken, and are therefore important to consider in the context of the nuclear-uranium debate.

The two main UNSCEAR studies on normalised global radiation doses from the nuclear industry are compiled in Table 2. Regardless of which timeframe or report is adopted, the UNSCEAR analysis clearly shows that uranium is an important contributer to the normalised global radiation dose from the nuclear chain, and perhaps could be the most significant. Although some critics argue the UNSCEAR data is somewhat pessimistic, a detailed analysis of radon releases from Australian uranium projects [Mudd, 2005e] suggests that the UNSCEAR assumptions are somewhat reasonable.

Table 2 – Long-term radiological exposure of the nuclear fuel chain (UNSCEAR analyses)

Stage of the Nuclear Fuel Chain		**Collective Effective Dose Committed per Unit Energy Generated (person.Sv/GWe.yr)**					
UNSCEAR Report Period		(1993)	(2000) '70-79	(2000) '80-84	(2000) '85-89	(2000) '90-94	(2000) '95-97
Local and Regional Component							
Mining, milling & tailings		1.5	0.238	0.238	0.238	0.238	0.238
Fuel fabrication		0.003	0.003	0.003	0.003	0.003	0.003
Nuclear reactor operation		1.3	3.2	0.9	0.46	0.45	0.44
Reprocessing		0.25	8.5	1.9	0.17	0.13	0.12
Transportation		0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total		**3.15**	**11.94**	**3.04**	**0.87**	**0.82**	**0.81**
Global Component (including solid waste disposal)							
Tailings (over 10,000 years)		150	7.5	7.5	7.5	7.5	7.5
Reactors	Low-level waste	$5x10^{-5}$	$5x10^{-5}$	$5x10^{-5}$	$5x10^{-5}$	$5x10^{-5}$	$5x10^{-5}$
Reactors	Intermediate waste	0.5	0.5	0.5	0.5	0.5	0.5
Reprocessing solid waste disposal		0.05	0.05	0.05	0.05	0.05	0.05
Globally dispersed radionuclides		50	95	70	50	40	40
Total		**200.5**	**103**	**78**	**58**	**48**	**48**

References : Table 53, pp 200 [UNSCEAR, 1993]; Table 45, pp 284 [UNSCEAR, 2000].

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 decreases the radon flux and load after rehabilitation while at others the data is less convincing (possibly increasing).

The UNSCEAR 1993 report [UNSCEAR, 1993] uses either 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 extent the mill also. 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 3 and 4, with more detailed data and estimates presented for the Ranger project in Tables 5 and 6. A more comprehensive analysis of radon fluxes and loads was recently prepared by [Mudd, 2005e].

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 [Mudd, 2005d]. 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) [Storm & Patterson, 1999], although as the data in Table 3 shows, the post-rehabilitation radon flux is less than 100 (or only 10^{2}) times lower. The UNSCEAR radon data for (an apparently unrehabilitated) Nabarlek 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 [Nielson & Rogers, 1986], 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 [WISE-UP, 2005]. 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) [Mudd, 2005d].

Table 3 : Radon fluxes and loads from select uranium mining and milling sites in Australia [adapted from Mudd, 2005e]

	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 / R (D)	~30	~0.24%	5 / 0.12	130 / 3
Jabiluka, NT (Mine Valley)	PM	-	-	0.046	-
Jabiluka, NT (Proposed Haul Road)	PM	-	-	0.025	-
Nabarlek, NT	PM		-	3.7-44.0	-
Nabarlek, NT	R (D)	~5	-	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 4 : Measured radon flux properties at Ranger and Nabarlek [adapted from Mudd, 2005b]

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 5 : Pre-mining calculated radon fluxes and loads from the Ranger ore zones [adapted from Kvasnicka & Auty, 1994]

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 6 : Progressive estimates (GBq/day) of combined radon loads from the Ranger project [Mudd, 2005d]

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.

Although the above tables and analysis are somewhat brief (see Mudd, 2005e for a more complete compilation), 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 UNSCEAR approach, which assumes tailings as the primary source of radon, is therefore limited and inadequate and needs to be expanded to include other sources such as waste rock and contaminated areas.

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 mineralisation (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 7, though it is not as comprehensive as desired. In general, most of this data is derived from exploration surveying and is not neccesarily obtained for environmental studies.

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 7 : Background gamma counts at select sites within the Alligator Rivers Region [Mudd, 2005d]

	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	90x90 m
Ranger 1 & 3	1,460->4,000	~30->80	4	6.5x1.5 km	30-250	6x0.5 km
Ranger 9 / 68	-	1	None	-	1 / (radon) †	-
Jabiluka 1	-	1	None	-	2	105x45 m
Jabiluka 1					1.5	80x40 m
Jabiluka 2	-	1	None	-	1	-
Nabarlek	700-1,960	~20-65	2	0.5x1.8 km	50	0.15x1.5 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 [Mudd, 2005b] :

(1) **Nabarlek** [see Martin, 2000] – mineral exploration and environmental surveys were used to estimate an average pre-mine gamma dose rate of about 0.18 μGy/hr. Detailed post-rehabilitation surveys have been undertaken, based on correlation of aerial and ground radiometric surveys, with the average gamma dose rate being derived at 0.27 μGy/hr. The gamma dose rate above the former ore zone has been decreased by about half but 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' [Lowson *et al.*, 1998] can be traced downstream in the Finniss River for many kilometres. There is no published aerial or ground gamma surveys for Rum Jungle and the surrounding region, 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 considerably 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 ranging from 0.14 to 1.4 μGy/hr (as well as radon) [Mudd, 2005a].

(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 from 0.33 to 6.0 μGy/hr through further erosion and dispersal [Mudd, 2005b].

(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 [Mudd, 2005b].

Although the examples quoted do not represent acute or immediately dangerous situations, from an environmental perspective these 'chronic' and perhaps permanent increases are of legitimate concern. This is due to the fact that increased gamma means invariably a higher presence of radionuclides in near-surface materials – giving rise to the potential elevated radionuclide loads reaching ecosystems. 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. Water 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 [Fox *et al.*, 1976 & 1977] 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 [eg. Kraatz & Applegate, 1992; Kraatz, 1998].

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 [Mudd, 2005b], with a concise summary in [Mudd, 2002]. 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 8).

Table 8 : Finniss River water quality, downstream of Rum Jungle, 1992/93 (μg/L) [Kraatz, 1998]

(† 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***

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 [Mudd, 2005d].

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 [Mudd, 2001a, 2005b, d].

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 or '009'), 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 from Retention Pond 2 (RP2) to Magela Creek, and, although winning the court case against the downstream traditional owners (who were clearly opposed), Ranger withdrew the application and did not proceed.

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, clearly unacceptable environmental impacts. The levels are derived using the methodology in the revised Australian Water Quality Guidelines [ANZECC & ARMCANZ, 2000]. In general, the aim is to prevent water quality deviating significantly from background (or upstream) concentrations by deriving the trigger values based on statistical variation or using local ecotoxicological data. The criteria for Ranger and Jabiluka are summarised in Table 9, 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 (especially given the weakness of baseline data prior to development). 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 9 : Annual downstream water quality summary fand criteria or Ranger and Jabiluka [compiled from Mudd, 2001a, 2005b, d; OSS, 2001; NTSA, various; leGras *et al.*, 2002]

			pH ‡	EC ‡	Mg ‡	SO_4 ‡	NO_3	Mn	^{226}Ra	U
			-	μS/cm	mg/L	mg/L	mg/L	μg/L	mBq/L	μg/L
1979-01	Ranger	Crit. †	ND	ND	10	19	0.6	24	13 §	3.8
2001/02 Wet	Ranger	Focus #	5.84-6.50	22	(use EC)	(use EC)	ND	11	>10	0.30
		Action #	5.51-6.83	30				19	>10 [1]	1.90
		Limit #	5.18-7.16	43				37	>10 [2]	5.8
2000/01 Wet	MC-U	Ave-rage	5.93	10	0.48	0.28	ND	4.96	ND	<0.1
	MC-D		6.02	12	0.72	0.73		4.35	3-20	0.1
2001/02 Wet	Jabi-luka	Focus #	4.61-5.31	15	0.37	0.60	0.30	ND	ND	0.02
		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 Wet	SC-U	Ave-rage	4.70	9	0.30	0.60	0.15	4.11	3-9	0.014
	SC-D		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. # These values are reviewed annually, with newer values recently approved.

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, agencies and companies is clearly not in step with community expectations [compiled from Mudd, 2001a, b, 2002, 2005b, d]. 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. There remains considerable scientific investigations to undertake to begin to address the long-term environmental protection of groundwater systems from the known and potential impacts of various forms of uranium mining.

6. Challenges for Future Uranium Milling in Australia

At present, the only conventional uranium mill in operation is Ranger. The Olympic Dam metallurgical plant is highly complex due to the polymetallic nature of the ore (although the uranium section is similar in principal to Ranger, it is only a segment of the overall facility). The Beverley plant is an unconventional acid in situ leach (ISL) mine.

At present knowledge, there are very few uranium projects which could employ relatively straight forward conventional milling technology (eg. Koongarra, Jabiluka, Kintyre – these projects face intense community opposition and still lack all necessary legal approvals).

For many other uranium projects around Australia the nature of their ore mineralogy demands the use of unconventional and experimental approaches. The two primary issues in this regard are the highly refractory nature of many prospects or the need to use alkaline milling.

6.1. Calcrete-Carnotite Uranium Ores

In Western Australia, there are numerous ‘calcrete’ sedimentary systems which host carnotite uranium mineralisation [see IAEA, 1984; Brunt, 1990; Cameron, 1990]. Due to the high alkaline content (ie. the calcrete) the use of acid leaching would require considerable quantities of acid – thereby necessitating the use of alkaline leaching. There is some experience overseas in milling calcrete ores (eg. USA, Canada) [eg. Butler, 1972], however, almost all of these sites are long in the past.

To date in Australia, there has been no commercial uranium mill built to process calcrete uranium ore. The only real experience is the relatively small Kalgoorlie metallurgical pilot mill (a 1 t/hr plant) built to test the treatment of Yeelirrie ore in the early 1980’s. Apparently some 13,000 t of ore was treated and produced approximately 9 t U_3O_8 – giving a yield of just 0.07% U_3O_8 [Mudd,2005e]. Compared to the average ore grade of 0.15% U_3O_8 [Cameron, 1990], this suggests a recovery of less than 50% (especially if higher grade ore at >0.2% U_3O_8 was used in this pilot testing, which is highly likely given common industry practice).

In general the use of alkaline milling is presently uncommon across the global uranium industry, as it is normally seen as slower and less efficient than acid milling. Recent experience at the Lodève mill in France involved the use of high temperature and pressure in alkaline milling [eg. IAEA, 2000] – somewhat analogous to the advent of high pressure acid leaching (HPAL) technology recently employed for nickel laterite ores. The processing costs for Lodève were high [IAEA, 2000].

Any development of calcrete uranium ores in Western Australia will therefore almost certainly involve the use of technology which is less certain than acid leaching used in various ways at Ranger, Olympic Dam and Beverley. This may also lead to higher capital costs for an alkaline mill, though whether that could be offset by possibly cheaper mining costs is entirely speculative.

6.2. Refractory Uranium Ores

Another major group of uranium prospects in Australia, primarily in South Australia and Queensland, are those containing highly refractory mineralisation such as brannerite and davidite (and to a lesser extent zircon) [eg. Henley *et al.*, 1972]. That is, conventional acid or alkaline milling technology is not able to achieve low cost uranium extraction from such minerals. This includes most deposits in the Mt Isa-Clonclurry belt in Queensland as well as the Olary Ranges region of South Australia. These deposits were discovered during the uranium prospecting boom of the mid-1950's and were immediately recognised as highly problematic to develop; for example :

- **Crocker's Well** [see King, 1954; Whittle, 1954] – discovered by South Australian government geologists in 1951 during regional radiometric survey work in the vicinity of Radium Hill; initial mineralogical/metallurgical testing showed extremely refractory uranium mineralisation (mainly absite, also known as thorian brannerite due to the higher thorium content).
- **Valhalla** [adapted from Henley *et al.*, 1972; Goldney *et al.*, 1972; McKay & Miezitis, 2001] – discovered in 1954 by prospectors, the ore is refractory (brannerite and zircon), includes a high proportion of alkaline minerals (mainly calcite) and defies conventional milling. Some recent testwork in the late 1990's included radiometric sorting and the use of two-stage high temperature acid leaching (250ºC). This testing apparently achieved a uranium recovery of 90% though it remains highly uncertain if such a complex mill could be cost competitive – no such precedent exists for this type of uranium milling in Australia (with limited experience globally).
- **Skal**, **Anderson's Lode** – *similar to Valhalla*.
- **Olympic Dam Mega-Expansion**[1] – The proposed major expansion (again) of Olympic Dam is presently looking to develop a considerable open cut based on the larger but lower grade mineral resources available south-east of current underground mining operations. Based on the most recently available ore estimates stating some 4 billion tonnes, the copper and uranium grades decline by about half from current ore mined and milled[2]. A critical issue associated with the changes in ore grades is that the metallurgical requirements alter significantly. For copper, the copper-to-sulfur ratio changes leaving the existing metallurgical complex unworkable from an economic view. For uranium, the mineralogy moves from about one-third brannerite to about one-half (this explains the historical uranium extraction of around 65%). During public relations for the mega-expansion, it has been suggested that recoveries could be increased to 85% - yet no discussion of the increased refractory nature of the ore has been alluded to.

7. Australia's Uranium Resources in Context : Economic & Otherwise

There are without doubt abundant uranium resources in Australia. The growth of these resources over time is shown in Figure 2. The 1970's exploration boom is clearly evident, followed by an increase between the mid-1970's to the mid-1980's (since this time no substantive increases have been recorded). This latter increase is largely attributable to Olypmic Dam, and the latest economic resources estimate for that project would suggest that a further increase in Australian resources is likely in the next edition of the OECD Red Book due in 2006 [OECD-NEA & IAEA, various].

A critical figure for the current debate on uranium resources is that despite the large quantity of identified resources, approximately 97% of Australia's lowest cost resources (the <US$40/kg U category) are contained within six deposits [OECD-NEA & IAEA, 2004] – Olympic Dam, Jabiluka, Ranger, Yeelirrie, Kintyre and Koongarra (~1,600, 163, 63.5, 52.5, 36 and ~17 kt U_3O_8, respectively).

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[1] See Mudd, G M, 2005, *Submission to House of Representatives Inquiry on Uranium Resources*. May 2005, In Progress, find through www.aph.gov.au ; also see the transcript for the Melbourne hearing (19 August 2005).
[2] Based on [Mudd, 2005b], current ore grades for ODam are about 2.3% Cu and 0.063% U_3O_8 (2004 to 2005 milling). Mineral resources reported by [WMC, 2004], and more recent media releases and reports, state resources at 3,980 Mt ore grading 1.1% Cu, 0.04% U_3O_8 and 0.5 g/t Au (see WMC Resources Media Release, 14 April 2005).

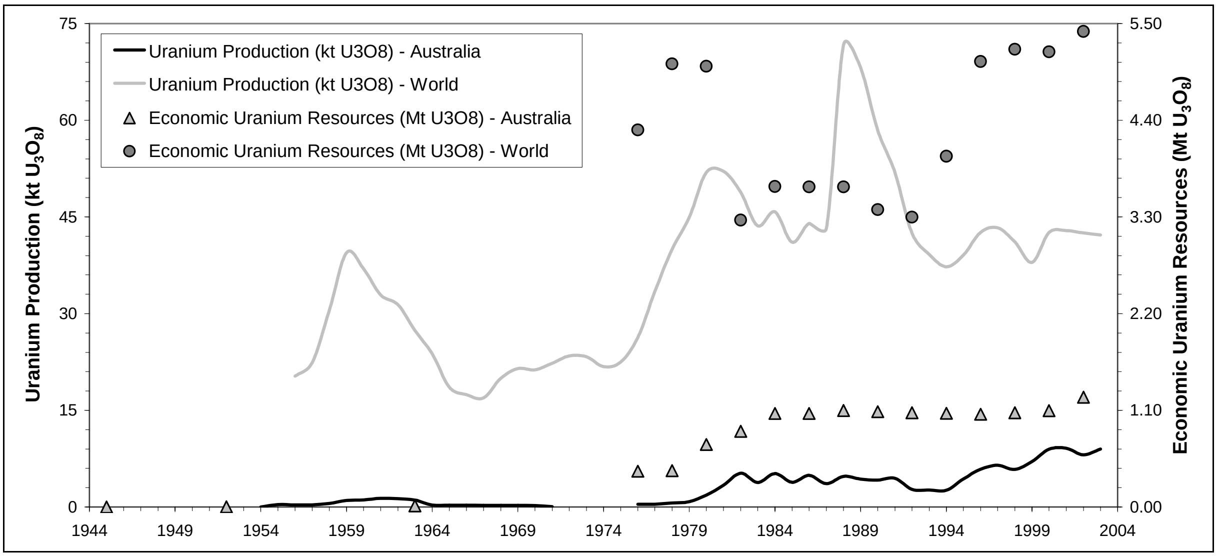

Figure 2 : Uranium production and resources – Australia and World [Mudd, 2005f]

Some basic points need to be highlighted with regards to each of these projects :

— **Olympic Dam** – There is potential to significantly increase production from Olympic Dam in the long term, although its scale gives rise to long lead times. Given the most recent ore estimate containing some 1.6 Mt U_3O_8, Olympic Dam could theoretically sustain annual production of 15,000 t U_3O_8 for more than a hundred years (subject to ongoing political support, copper and uranium markets, community concerns, etc). The expansion will face major challenges on low cost energy, securing water rights, tailings and waste rock management, metallurgy and the like.

— **Jabiluka** – This project has been vehemently opposed by the Mirarr traditional owners and the Australian community. At present the site is under long-term care and maintenance (LTCM). In early 2005, the Mirrar and companies[3] signed a formal agreement covering the LTCM whereby the Mirarr have a complete right of veto over ***any*** future development at Jabiluka. The project is therefore extremely unlikely to proceed for the forseeable future.

— **Ranger** – There are only several years left to operate Ranger and it is highly unlikely to expand production in this timeframe (though it is likely to operate above nominal design capacity).

— **Yeelirrie** – The project is now owned by BHP Billiton following their successful takeover of WMC Resources in mid-2005. The deposit, though large at 52,500 t U_3O_8 [Cameron, 1990], is of the calcrete-carnotite type. This makes the deposit potentially more expensive to develop due to the more difficult nature of alkaline milling. The trial mines, undertaken in the early 1980's to support the pilot milling/metallurgical research at Kalgoorlie, were rehabilitated in 2004 (apparently involving some 35,000 t of ore; no data has been reported publicly). At present, there are no indications that either WMC or now BHP have active plans to develop Yeelirrie.

— **Kintyre** – This prospect is in a very remote corner of north-east WA. Although experimental metallurgy has been conducted (apparently successfully), the project is owned by Rio Tinto Ltd (current majority owners of Ranger and Jabiluka). At present, Rio have not shown any recent interest in developing Kintyre. Its remoteness and other technical aspects (eg. water, energy, infrastructure, Rudall River National Park, etc) all point to significant uncertainty. The Martu traditional owners have consistently opposed any development at Kintyre.

— **Koongarra** – This is perhaps the most difficult of any potential future uranium project in Australia. The deposit is high grade but moderate in size; being 1.83 Mt of ore grading 0.795% U_3O_8 for 14,550 t U_3O_8 contained [Snelling, 1990]. There is no land rights agreement in place

[3] The Jabiluka and Ranger uranium projects are owned and operated by Energy Resources of Australia Ltd (ERA), which in turn is 68.4% owned by Rio Tinto Ltd (Rio).

(required under the *Aboriginal Land Rights Act 1976*], the current mineral lease is inappropriate for the proposed layout of the project, it was categorically opposed by the Ranger Inquiry [Fox *et al.*, 1977] and has been agreed to be incorporated into Kakadu National Park by the Commonwealth Government (though exceedingly little has been done in this last regard). Additionally, the project is adjacent to and would be easily visible from the Nourlangie Rock Art site – one of the most popular tourist sites in Kakadu. The present owner, French company Cogema, have aspirations to develop the project, but any attempt for Koongarra clearly has to overcome numerous extremely difficult obstacles.

As can be seen from this above list, most future uranium production in Australia always comes back to Olympic Dam. A detailed assessment of the data in [OECD-NEA & IAEA, 2004] would suggest that most other deposits in Australia are within higher cost categories (eg. <US$80/kg U and <US$130/kg U) (see page 80). Therefore, in contemplating potential new uranium projects in Australia, the issues raised earlier such as milling challenges would seem to be already acknowledged by some experts within the industry.

In addition to the fundamental issues of technical project risk, there are a number of other issues which must be considered in assessing the viability of these resources :

(1) **State Policies** – All state and territory governments in Australia have clear policies against ***new*** uranium mines. In some states this is by legislation (eg. New South Wales, Victoria) while in others it is through a policy position taken to and affirmed by an election. For South Australia, the expansion of the existing Olympic Dam project would be allowed, but a satellite deposit near the Beverley acid leach project would most likely be considered a 'new' mine and therefore not up for approval under state policy.

(2) **Community Opposition** – There is a long history of significant community concern and opposition to the nuclear industry (even as early as the 1940's; see Bowker, 1948). Despite the previous booms in uranium exploration and development in the 1970's, 1980's, 1990's and the present efforts, only four projects have been opened commercially – including just Beverley since 1996 and the removal of the Labour Three Mines Policy.

(3) **Markets** – Almost all uranium is sold under long-term contracts (due to the long lead times involved with conversion, enrichment and fuel manufacture), of which many long-term contracts are leveraged in some way to the spot price. The spot price also only represents a small volume of the global market and is therefore not an ideal indicator of market issues due to these two factors. Given the small nature of most Australian uranium deposits (outside those discussed above), new proponents will have to break into an extremely difficult market to obtain contracts – a feat made harder by the fact they will only ever be small, short-term producers.

(4) **Demand** – It seems clear that some basic points are being ignored or at least glossed over on uranium supply-demand. Firstly, most of the nuclear power reactors around the world are in western countries, mostly built between the late 1960's to mid-1980's. As such, many of these reactors are facing the end of their useful operating life sometime in the coming one or two decades. There are some reactors which are winning approvals to extend their operating licence (though this is not without major risks), but there are also other reactors which are being closed down earlier due to high operating costs. There are no plans at present to replace these reactors, let alone build new reactors to expand nuclear production. Overall, this will lead to strong and sustained downward pressure on uranium demand over this period (also affecting the spot price and thus many long-term contracts). Secondly, the rate of building reactors elsewhere in the world, such as China and India, in no way replaces the same capacity due to be lost in the western world over this same time period. In the long-term, it is not possible to envisage a realistic scenario where there will be a strong and sustained increase in uranium demand.

(5) **Weapons U** – As with the 1990's, there is the future possibility of additional enriched uranium being made available to the nuclear power industry through the decommissioning of nuclear weapons. Given the large stocks of weapons still menacing the world and the global concerns on proliferation risks, this is clearly an important issue.

8. The Final Test : Rehabilitation

The final test on the issue of the environmental impacts of uranium mining is the long-term performance of minesite rehabilitation. It is widely acknowledged by all stakeholders that the 1950's-60's era was not an example of good rehabilitation practice (though some projects were considerably worse than others). The modern era since 1976 has seen improvements with regards to planning and implementation of rehabilitation, though some major issues still remained unresolved. Additionally, the monitoring of the long-term performance of the sites which have had rehabilitation is leading to fundamental questions concerning long-term integrity of current sites. Examples include[4] :

- **Rum Jungle** – Abandoned in 1971, the site produced a wide-reaching legacy of water pollution in the Finniss River, due mainly to acid mine drainage and poor tailings, waste rock and water management. The site was rehabilitated in the early 1980's and was monitored by the NT and ANSTO until about 2002, from which time only limited monitoring has occurred. Based on the monitoring data and reports [see Allen & Verhoeven, 1986; Kraatz, 1992; Kraatz & Applegate, 1998; Pidsley, 2002], it is clear that the rehabilitation has not been as ideal as hoped. This can be argued to be related to design and construction issues but it also raises fundamental questions concerning the long-term effectiveness of rehabilitation works in the tropics. Based on the last reported data, infiltration is increasing through the covers and significant loads of metals could not be accounted for based on surface water concentrations and flows alone – suggesting the importance of the polluted groundwater as a slow but significant source of metals for the Finniss River system.
- **Mary Kathleen** – Finally closed in 1982, the site won an engineering excellence award in 1986 for rehabilitation. One of the primary concerns at this time was seepage through the old tailings system. Recent research has shown this concern to be legitimate, as elevated seepage waters are emanating from the tailings dam and discharging salts, metals and radionuclides into the local creek [see Costelloe et al., 2000; Lottermoser *et al.*, 2003].
- **Radium Hill** – Closed in 1961, the site has required maintenance and surveillance. There are ongoing issues of erosion, a radioactive waste dump, and remaining mill and other infrastructure to be removed.
- **South Alligator Valley** – After the proposed Coronation Hill mine was stopped in 1991, attention turned to the rehabilitation of the numerous old mines in this region of Kakadu National Park. The issue rose to brief prominence in late 2000 when it was revealed that remnant tailings were being eroded by a new road alignment and being dispersed by passing traffic. Despite a requirement to have all rehabilitation finished by 2006, no works or even impact assessments have been completed to date (though some investigations, planning and consultations have occurred). The state of the old Moline uranium-gold-base metal tailings is unknown (they were later covered by some 3 Mt of gold tailings over 1988-1992).
- **Nabarlek** – Closed in 1988 and rehabilitated by 1995, the site has been a major test for rehabilitation in the Kakadu region. As noted previously, the radon flux is somewhat lower than pre-mining rates (though not as low as originally predicted) but the gamma dose rates are significantly higher over a much larger area than the original ore body. The site, as above, has ongoing issues with weeds, erosion, maintenance and remaining infrastructure.

This brief review (and the more detailed technical reviews they are extracted from) highlights the major challenges facing demonstrated long-term performance of rehabilitation. These problems also raise the same questions across the mining industry as well as their increased significance for the uranium industry. The most difficult issue, perhaps, is that of criteria and standards for rehabilitation. At present there are some clear objectives, such as tailings management and radiation levels, but all other aspects are specific to particular project – and are often ardently contested. It is important to emphasize that any future mine will continue to be judged by the performance of older projects.

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[4] A detailed history and critique of all sites quoted is given in [Mudd, 2005b].

9. 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 this work which are pivotal to any debate on uranium mining.

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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