A Compendium of Radon Data For the Rehabilitation of Australian Uranium Projects

G.M. Mudd
Institute for Sustainable Water Resources, Department of Civil Engineering, Monash University, Clayton, Australia

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ABSTRACT: The release of radon gas and radon progeny from uranium projects is a major issue during operation as well as for the design of rehabilitation works. In Australia, there have been a number of pre-mining radon flux studies as part of the environmental investigation and potential development of recent uranium projects. There is also an increasing amount of operational data on radon fluxes and loads from various aspects of projects, such as tailings, waste rock and mills. Thus there exists much useful measured data which can be used to assess the design radon flux and load targets for rehabilitation. The main projects for which radon data exists includes Ranger, Olympic Dam, Beverley, Honeymoon, Jabiluka, Yeelirrie, Lake Way, Koongarra, Moline, Coronation Hill, Rockhole, Nabarlek, Rum Jungle, Port Pirie and Ben Lomond. To date, much of this data has not been thoroughly evaluated. The need to compile and assess this data is twofold. Firstly, to assess the loads released from uranium production as an input into life-cycle analyses of the nuclear fuel cycle, such as those undertaken by UNSCEAR and industry groups. Secondly, there is a need to set suitable design standards for radon flux for the rehabilitation of former and current uranium projects. This paper will present such a detailed compilation of radon fluxes and loads which can then be used as the basis for both life-cycle analyses as well as setting appropriate site-specific rehabilitation criteria for radon. The implications for former and current projects is then discussed as well as future data needs.

1 INTRODUCTION

The release of radon gas and its radioactive decay progeny is an important aspect of the mining and milling of uraniferous ores. The exposure to elevated radon progeny is a well established cancer risk, and can be important for uranium mine workers as well as some communities in particular geologic regions. don releases. Another aspect is the design criteria set for the rehabilitation of former and current uranium projects. Thus it is important to assess the actual release rates and loads of radon from uranium mining and milling projects as a thorough basis for these various types of assessments. This paper presents the compilation of radon data for several Australian uranium projects, thereby providing the basis on which to conduct various types of assessments and set realistic rehabilitation criteria for radon fluxes.

2 RADON RELEASES AND DATA SOURCES

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has presented various analyses of the radon loads due to uranium mining and milling and its global radiological consequences (eg. (UNSCEAR, 1993, 2000). In general, they used data direct from various mines and companies or assumed data based on known ore grades and the like. The cumulative global radiological exposure per reactor year of operation was estimated at 150 and 7.5 person.Sv/GWe.year by (UNSCEAR, 1993, 2000), respectively.

The radon data and assumptions used by UNSCEAR in their analyses have been questioned by (Chambers *et al*, 1998; Frost, 2000). In general, these authors assert that the UNSCEAR analyses adopt the most pessimistic values and that more realistic radon release scenarios suggest that the exposures are considerably lower. For example, (Chambers *et al*, 1998) argues that the long-term radiological exposure due to radon is 0.96 person.Sv/GWe.year, very much lower than the latter UNSCEAR estimate of 7.5 person.Sv/GWe.year.

The various analyses noted above, however, are still based on a limited survey of the literature and do not take into account the numerous studies which provide actual field data for radon releases from several uranium projects. The data for Australia in particular is sometimes reliant on written advice from specific operations only and appears to use only a minimal degree of field-measured data.

Radon release is a complex process, depending on the parent ^{226}Ra activity, physical characteristics, mineralogy, barometric pressure and especially moisture content (Strong & Levins, 1982; Hart, 1986; IAEA, 1992). For a given uranium project, the principal sources of radon are ore and waste rock stockpiles, mines, mill, tailings dams and retention ponds. Sites of significant radium contamination may also be important. The radon loads released from different projects will therefore vary widely, emphasizing the need for site-specific data.

Some important issues not sufficiently addressed to date are the difference between natural and pre-mining radon fluxes and the cumulative nature of these changes. It is this overall cumulative difference in radon release rates which should ultimately be used in setting rehabilitation criteria and performing life-cycle analyses of nuclear energy.

The principal sources of data which can be used to provide more realistic estimates of radon flux include : (i) environmental impact statements (EIS); (ii) research projects and theses; (iii) statutory monitoring; (iv) engineering and other investigations. For Australia, most of these data sources are publicly available, however, some data is known to exist for some sites but is not public (eg. Mary Kathleen). A brief review was presented by (Sonter *et al*, 2002), though it was not intended to be wide-ranging. A detailed compendium of radon flux and load data will now be assembled and analysed.

3 DETAILED RADON FLUXES

3.1 *Baseline Radon Flux*

Due to the natural abundance of about 2.7 mg/kg uranium in soils and rocks (Titayeva, 1994; Langmuir, 1997), there is a global average radon flux from soils of about 0.015 to 0.023 Bq/m^2/s (UNSCEAR, 1982). The mean radon flux from Australian soils is 0.022 ± 0.005 Bq/m^2/s, with a ^{226}Ra activity of 28 mBq/g (Schery *et al*, 1989).

3.2 *Uranium Mining and Milling in Australia*

The commercial production of uranium in Australia began in 1954, and is currently about 9,000 t U_3O_8 per year. Small but determined attempts to develop a radium mining industry between 1906 to 1934 failed to lead to commercial uranium production (Mudd, 2004b). To date there has been a total of 11 uranium mills, including pilot projects, and 31 mines of various scale supplying ore to adjacent or nearby mills or for pilot milling and exploration work. The location of Australian uranium project sites and deposits is shown in Figure 1, with a compilation of production data in Table 1 and deposit size in Table 2.

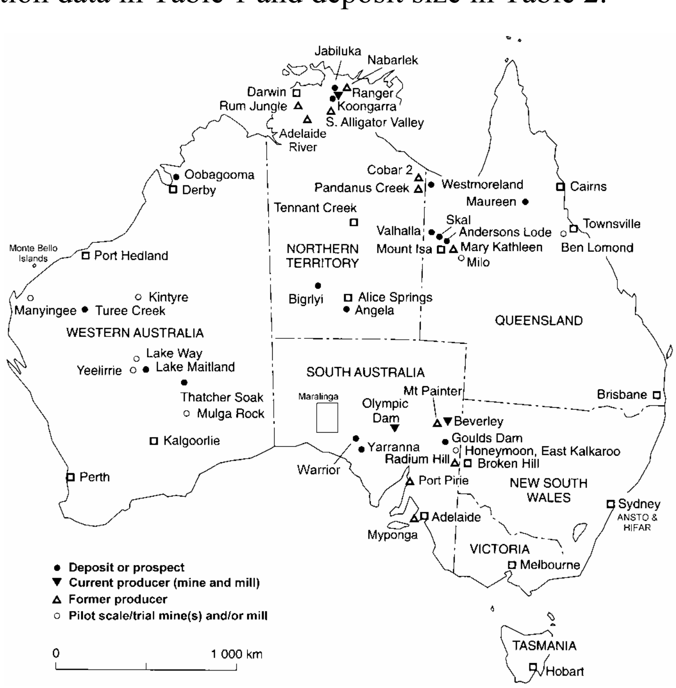


Figure 1 Australian uranium deposits and projects

Table 1. Australian uranium production to March 2004 (Mudd, 2004a)

Project	Time	Ore t milled	Ore %U_3O_8	Production t U_3O_8	Tailings %U_3O_8	Tailings ^{226}Ra (Bq/g)	t Waste Rock/ Low Grade Ore
Olympic Dam [#]	1988-	69,228,678	0.077	33,725	0.028	8.07	~8,945,000
Ranger [#]	1981-	26,899,000	0.31	75,284	0.033	12.5	~95,750,000
Nabarlek Nabarlek [HL]	1979-88	597,957 157,000	1.84 ~0.1	10,955	0.036 ~0.02	191.1 5.19	2,330,000
Beverley [ISL,#]	2001-	~17,000 ML	~0.18	2,009	nd	nd	nd
Honeymoon [P,ISL]	-	~900 ML [‡]	~0.12	29.4	nd	nd	nd
Mary Kathleen Mary Kathleen	1958-63 1976-82	2,710,483 6,200,000	0.156 0.10	4,092 4,801	~0.01 ~0.02	16.2 10.4	~22,000,000
Moline [SAV]	1956-64	135,444	0.46	716	0.070	47.5	nd
Rockhole [SAV]	1959-62	13,418	1.11	140	0.066	115.3	nd
Radium Hill [†] / Port Pirie [†]	1952-62	822,690 [†] ~153,400 [†]	~0.12 [†] ~0.74 [†]	852	~0.02 [†] ~0.10 [†]	0.52 [†] 76.8 [†]	nd
Rum Jungle	1954-71	1,500,000	0.35	3,530	0.086	33.7	~18,027,300
Trial mines	-	»10,000	~0.92	nd	nd	~95.5	»150,000
Radium Hill [R]	1906-32	>2,150	~1.4	~7	nd	nd	nd
Mt Painter [R]	1910-34	~933	~2.1	~3	nd	nd	nd
	TOTAL	108.374 Mt	0.154	136,188	0.030	16.0	»149.2 Mt

[#] Still operating; [HL] Heap Leaching; [ISL] In Situ Leach (solution volumes in ML); [P] Pilot project; [‡] Assuming 2.5% bleed; [SAV] South Alligator Valley; [†] 975 kt ore was pre-concentrated at Radium Hill, with the the 153 kt concentrate processed at Port Pirie; [R] Radium mining; nd No Data.

Table 2. Summary of uranium deposit sizes (Mudd, 2004a, d)

Uranium Deposit	Ore Mt	U_3O_8 %	Dimensions (m) D	L	W	Th
Honeymoon	2.75	0.12	~110	1,000	400	4.3
Beverley	12.2	0.18	~110	4,000	400-750	20-30
Olympic Dam	2,950	0.04	350	5,000	400-2,300	400
Ben Lomond	2.98	0.23	50-75	750	150	100
Ranger 1	19.78	0.32	1-20	500	300	185
Ranger 3	30.76	0.24	20-30	900	500	25-100
Nabarlek	0.755	1.48	2-5	230	10	85
Jabiluka 1	1.36	0.25	25	350	225	<35
Jabiluka 2	31.1	0.53	80-120	1,100	400	<135
Koongarra 1	1.83	0.8	2-25	450	30-100	100
Koongarra 2	0.77	0.3	50-250	100	30-100	<200
Coro. Hill §	0.34	0.54	150	??	??	??
Lake Way	5.98	0.09	2-10			1.5
Yeelirrie	35.2	0.15	2-8	9,000	<1,500	3-4

§ Coronation Hill was 1 of 13 mines within the South Alligator Valley. D Depth; L Length; W Width; Th Thickness (approximate only).

3.3 *Ore Milled and Tailings Production*

Based on the data in Table 1 (but excluding ISL), the production of each tonne of Australian uranium (as U_3O_8) requires about 808 t of 0.154% U_3O_8 ore and 1,112 t of combined low grade ore and waste rock. The average specific radium activity is 16.0 Bq/g (assuming secular equilibrium and minimal losses) while the tailings contain residual uranium of about 0.030% U_3O_8.

An important aspect of the UNSCEAR analyses was the average area taken up by tailings, normalised to the area per annual energy output and assumed to be 1 ha/GWe.year (UNSCEAR, 1993). This is important due to the slow rates of radon diffusion in tailings. For a given mass of tailings, a thicker tailings pile will allow less radon to emanate into the environment than a thinner but greater area pile. A compilation of the areas and dry densities of the different tailings piles in Australia are given in Table 3, based on existing, proposed or as-rehabilitated scenarios. Conflicting data has not been able to be resolved, data approximate only.

The UNSCEAR analyses assumed 1.6 t/m^3 dry density – the same as that in Table 3. In practice, many tailings sites have a dry density lower than this, such as the above ground dam at Ranger at ~1.0 t/m^3 and Pit 1 averaging ~1.3 t/m^3 (Mudd, 2004d). The initial tailings dry density at Nabarlek (1980-85) was <1.0 t/m^3 but by the time of site rehabilitation in 1994 a density of about 1.3 t/m^3 can be estimated (Mudd, 2004d). The Olympic Dam tailings apparently achieve a density ranging from 1.6 to 2.0 t/m^3, averaging 1.7-1.8 t/m^3 (Mudd, 2004d). There is a lack of tailings density data at older sites; the values in Table 3 are best estimates.

Based on the data in Table 3, currently proposed rehabilitation strategies and the UNSCEAR figure of 250 t U_3O_8 per GWe.year, a normalised tailings production value of 1.2 ha/GWe.year can be estimated. Although rehabilitation works are planned for some sites (eg. Ranger), these changes are not expected to affect the calculated values significantly.

3.4 *Waste Rock and Low Grade Ore Production*

The total waste rock and low grade ore produced in Australia is mostly quantified, with minor uncertainty and missing data. Based on data in Table 1, at least 149 Mt has been excavated to date, with a probable maximum of about 160 Mt (data for underground and most older mines is generally not available). The principal sites are Ranger, Olympic Dam, Mary Kathleen, Rum Jungle and Nabarlek.

The available average uranium grades of the various stockpiles is compiled in Table 4. It must be assumed that waste rock at other former mines contains <0.02% U_3O_8. A small stockpile of 3 kt at Pandanus Creek is about 1% U_3O_8 (Mudd, 2004d).

Table 3. Uranium mill tailings pile data to end 2003 (Mudd, 2004d)

Project	Description of Tailings Facility	Status	Area ha	Mass t	Density - Dry (t/m^3)	Volume Mm^3	Depth (m)
Radium Hill	No. 1 Dam	Rehab'd	~8	~100,000	(unknown)	(unknown)	~ 2 ?
Radium Hill	No. 2 Dam		~32	723,000			~ 5 ?
Port Pirie	Surface dam	Rehab'd	~30	151,550			~ 2 ?
Rum Jungle	Surface deposition minus erosion R	Removed	34	~576,000	~1.7	~0.34	~1.0
Rum Jungle	In-pit (White's)	Rehab'd	11	~600,000	~0.6 (?)	~1.0	nd
Rum Jungle	In-pit (Dyson's)	Rehab'd	6	~500,000	~2.3 (?)	~0.22	nd
Mary Kathleen	Surface dam	Rehab'd	29	~8,900,000	nd	nd	nd
Rockhole	Surface deposition minus erosion R		~2	~12,000	nd	nd	nd
Moline	Surface deposition minus erosion R	-	18	~202,000	~1.2	~0.188	~1.0
Moline	Surface dam (as rehabilitated)	Rehab'd	~6	~208,000	nd	?	nd
Nabarlek	In-pit (including heap leach wastes)	Rehab'd	5	744,000 t	~1.3	~0.47	<65
Ranger	Interim surface dam R	Standby	117	13,624,000	1.0	13.6	11.6
Ranger	In-pit (Pit #1)	Operating	51	12,769,000	~1.3	9.8	-
Ranger	In-pit (Pit #3) #	-	~75	-	-	-	-
Olympic Dam	Current surface dam §	Operating	380	~65,363,000	1.6→2.0	~36.0	8.3
Olympic Dam	Proposed dam (likely to change)	-	720	(up to 2.9 Gt)	~1.75 average	-	-
		TOTAL – At Present	633 ha	104.26 Mt	~1.6 t/m^3	~65 Mm^3	~10.3 m

R Removed during previous rehabilitation works or planned removal in future; # Not in operation as yet (all surface tailings will be transferred to pits 1 and 3), about 38 Mm^3 expected; § About 5% of tailings is used for coarse backfill underground; nd No Data.

Table 4. Waste rock and low grade ore (Mudd, 2004a, d)

	Project	LGO Mt	LGO $\%U_3O_8$	WR Mt	WR $\%U_3O_8$	Area ha
Rum Jungle	White's	nd	nd	8.950	0.004	30.4
	Dyson's	0.0478	0.077	2.032	0.005	8.43
	RJCS	0.116	0.066	4.877	0.018	21.9
	Mt Burton	0.0035	0.072	0.254	nd	3.28
	Mt Fitch	nd	nd	0.020	nd	~0.5
	Intermed. §	nd	nd	1.727	0.005	6.85
	Nabarlek	0.157 HL	~0.05	2.33	~0.013	6 R
	Ranger ‡	35.646 ‡	~0.072	61.382 ‡	<0.02	~200
	Olympic Dam	nd	nd	8.945	nd	0 #
	Mary Kathleen	>0.566	nd	~22 †	nd	64
	TOTAL	>36.54	~0.072	~112.5	~0.01?	~341

RJCS Rum Jungle Creek South § Intermediate deposit mined for Cu only; HL Heap leached; R Removed during rehabilitation; ‡ Approximate only (conflicting data); # Backfilled underground; † Total.

Overall, the 1,112 t of low grade ore / waste rock produced per t U_3O_8 can be expected to have a grade of about 0.03% U_3O_8. The average mass is about 411 kt/ha, and assuming a typical waste rock density of 2 t/m^3 gives a height of about 20.6 m.

3.5 *Pre-Mining Radon Fluxes*

The available pre-mining radon flux surveys are compiled in Table 5. The pre-mining radon flux contours for the Koongarra deposit with the pre-mining radon activity in soil at Nabarlek are shown in Figure 2. In general, it is only deposits of sufficient size and shallow depth which give rise to an elevated radon flux at the surface. Some examples include Lake Way, Yeelirrie, Ranger and Nabarlek.

3.6 *Mining – open cut, underground and ISL*

There is only scattered data on the fluxes and loads of radon released from either underground or open cut uranium mining, compiled in Table 6. The EIS estimates for some proposed mines are included.

A difficult issue is the radon released by in situ leach (ISL) mines, currently in used at Beverley. It can be expected that the loads would be smaller than by conventional mining, however, it is also likely that during operation the loads would be above normal baseline for the region.

3.7 *Waste rock and low grade ore stockpiles*

As noted earlier, there is an increasing stockpile of waste rock and low grade ore being produced. The available data for radon fluxes and loads are compiled in Table 7, which is indicative only.

As expected, there is a notably wide variation in the radon fluxes and loads from waste rock, low grade and ore stockpiles. Some data may not be reliable, as the values seem either too high or low (eg. trial ore stockpile at Yeelirrie). Another example is Rum Jungle, where although a rehabilitation standard of 0.14 Bq/m^2/s was adopted, there was no survey following rehabilitation works (1982-86).

Given the wide variation and lack of data quality, it is not possible to obtain a clear correlation to derive any meaningful average radon load.

Table 5. Pre-mining radon fluxes from select Australian uranium deposits

Project	Period or Date of Survey	Area ha	Flux (min→avg→max) Bq/m^2/s	Load GBq/d	References
Kakadu region #	Various 1992-98	-	0.009→0.030→0.057	-	(Auty & du Preez, 1994; Todd, 1998)
Kakadu region #	July 2002	-	0.070 ± 0.002	-	(Akber *et al*, 2004)
Jabiluka 2	Sept.-Dec. 1992	-	0.046	-	(Auty & du Preez, 1994)
Jabiluka 2 (east)	Nov. 92 & July-Aug. 93	-	0.025	-	(Auty & du Preez, 1994)
Koongarra 1	June 1978	12.53	0.57→2.43→20.76	26.1	(Davy *et al*, 1978)
Koongarra 2	June 1978	-	<0.05	-	(Davy *et al*, 1978)
Nabarlek	Sept 1978	5	3.7→44.0 †	-	(Clark *et al*, 1981)
Nabarlek	June 1979	5	11.5→164.0 †	-	(Clark *et al*, 1981)
Nabarlek (baseline)	Aug 1999-Oct 2002	-	0.018 ± 0.007 (30 pts)	-	(Bollhöffer *et al*, 2003)
Ranger total	(calculated estimate)	245	1.78	377	(Kvasnicka & Auty, 1994)
Ranger 1	(calculated estimate)	44	4.1	156	(Kvasnicka & Auty, 1994)
Ranger 3	(calculated estimate)	66	2.5	143	(Kvasnicka & Auty, 1994)
Ranger 1-3 vicinity	(calculated estimate)	81	1.0	70	(Kvasnicka & Auty, 1994)
Honeymoon	April-June, 1980	-	0.033	-	(Whittlestone, 1980)
Honeymoon	1998	-	0.038	-	(SCRA, 2000)
Beverley	1980	-	0.044	-	(AMDEL, 1982)
Paralana Springs §	1980	-	10.6	0.54	(AMDEL, 1982)
Olympic Dam	June 1991-May 1992	-	0.005→0.025→0.035	-	(WMC, 1992)
Yeelirrie	November 1976	-	3.7	2,159	(WMC, 1978b)
Yeelirrie	1981	675	0.5→8	-	(Leach *et al*, 1983)
Yeelirrie	Early 1980s (various)	-	0.05→3.5	-	(O'Brien *et al*, 1986)
Yeelirrie	November 1976	-	~0.74	-	(WMC, 1978b)
Lake Way (inner &	4-17 September 1979	310	0.3	80	(Casteleyn *et al*, 1981)
outer mine area)	4-17 September 1979	390	0.126	42	(Casteleyn *et al*, 1981)
Lake Way baseline	4-17 September 1979	-	0.044	-	(Casteleyn *et al*, 1981)
Australian baseline		-	0.022 ± 0.005	-	(Schery *et al*, 1989)

Kakadu National Park (surrounding Ranger, Jabiluka, Koongarra and near Nabarlek); § About 15 km west of Beverley; † Only range given.

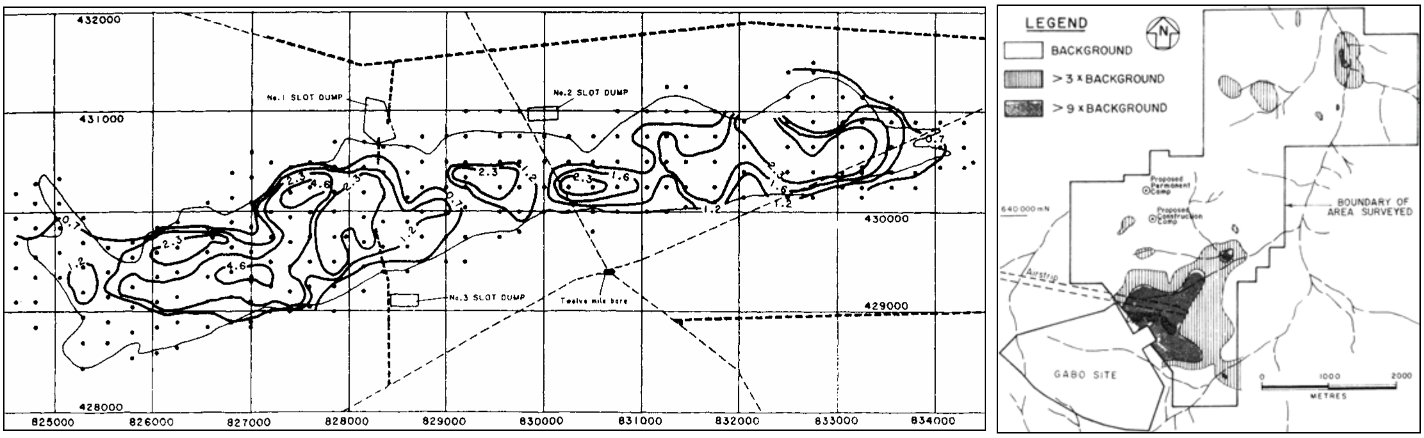


Figure 2 *Left* – Pre-mining radon flux (Bq/m^2/s), Yeelirrie uranium deposit, central Western Australia (Leach *et al*, 1983); *Right* – Pre-mining radon activity in soil (ratio only, background not given), Nabarlek uranium deposit, Arnhem land, NT (QML, 1979)

Table 6. Radon fluxes and loads from abandoned, operating, rehabilitated and proposed uranium mines

Project	Mine Type	Sta-tus	Description	Period of Estimate (est.)	Grade %U_3O_8	Flux Bq/m^2/s	Area ha	Load GBq/d	References
Ranger	OC	Op	Ranger Inquiry (1975-7)	~1975 est.					(Fox *et al*, 1977)
Ranger 1	OC	Op	Walls only (3 points)	Oct 2003		0.304 ± 0.085			(Akber *et al*, 2004)
Ranger 3	OC	Op	Rubble pile (9 points)	Oct 2003		1.680 ± 1.960			(Akber *et al*, 2004)
Ranger 3	OC	Op	Rocks (2 points)	Oct 2003		1.033 ± 1.423			(Akber *et al*, 2004)
Ranger 3	OC	Op	Pad area (25 points)	Oct 2003		2.533 ± 3.094			(Akber *et al*, 2004)
Jabiluka 2	UG	Pr	Calculated est. (EIS)	~1996 (EIS)	-	-	-	121	(Howes, 1997)
Jabiluka 2	UG	Op	Decline & cross-cuts	Jul-Aug 1999	1.15	~17.3	-	-	(Sonter, 2000)
Coro. Hill	UG	Ab	Old mining adit	Late 1980s	-	0.036 ± 0.057	-	-	(DM, 1988)
Coro. Hill	OC	Ab	Abandoned open cut	Late 1980s		0.67 ± 0.46			(DM, 1988)
Yeelirrie	OC	Pr	As proposed	1978 EIS est.	-	~4.7	606	2,463	(WMC, 1978b)
Yeelirrie	OC	Pr	Post-mining (proposed)	1978 EIS est.	-	~1.2	606	602	(WMC, 1978b)
Yeelirrie	OC	Pr	As proposed	1979 EIS est.	-	-	606	1,918	(WMC, 1979)
Koongarra	OC	Pr	As proposed	1978 EIS est.	-	-	-	23-57	(Noranda, 1978)
O. Dam	UG	Op	Operating (exploration)	1980-81	-	0.3→1→3		-	(Kinhill, 1982)
O. Dam	UG	Op	As proposed	1982 EIS est.	-	-	-	700	(Kinhill, 1982)
O. Dam	UG	Op	Operating (commercial)	Jun 92-May 93	~0.083	-		120	(Davey, 1994)
O. Dam	UG	Op	Operating (commercial)	~1996	~0.08	-		121	(Howes, 1997)
B. Lomond	OC	Pr	As proposed	1979 EIS est.	-	-	-	22.9	(Minatome, 1979)
B. Lomond	UG	Pr		1979 EIS est.				38.4	(Minatome, 1979)
B. Lomond	OC	Pr	As proposed (ore)	1983 EIS est.		10	1	8.6	(Minatome, 1983)
B. Lomond	OC	Pr	As proposed (waste rock)	1983 EIS est.	-	0.3	10	2.6	(Minatome, 1983)
B. Lomond	UG	Pr	As proposed	1983 EIS est.		-	-	3.2	(Minatome, 1983)

OC / UG Open cut / underground mine; Op Operating / Pr Proposed / Ab Abandoned.

3.8 *Uranium Ore Milling*

During the milling of uranium ore, radon can be released from dust, ore grinding, leach solutions, calcining and product packaging areas. To date, only total estimates for radon loads from mills have been made, almost entirely for EIS purposes for recent uranium projects. The data is compiled in Table 8.

3.9 *Radon From Tailings*

One of the most significant (and controversial) sources of radon from uranium mining and milling, both during operation as well as after rehabilitation, is that from mill tailings. The predictions for radon fluxes and loads have varied notoriously, depending on the chosen tailings management regime.

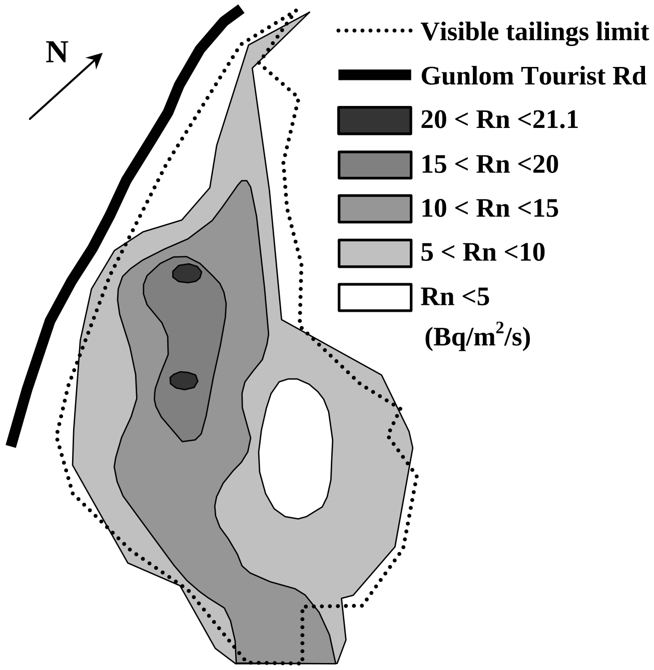
The available data for tailings-derived radon is compiled in Table 9, including the sites where some rehabilitation works have been undertaken to date. The radon emanation contours at the former Moline and Rockhole tailings are shown in Figure 3. In 1986, most of the Rockhole tailings were excavated and transported to Moline, which was also re-excavated with all tailings emplaced within a new gold tailings dam (Mudd, 2000). There is no known radon flux survey since this 1986.

The efficiency of water covers in reducing radon flux from tailings was a central issue during the Ranger Uranium Environmental Inquiry (Fox *et al*, 1977), and remains a subject of some conjecture. For example, (Chambers *et al*, 1998) state that the radon released from Ranger's tailings to be 'zero', while other estimates have ranged up to 4,000 GBq/day (Mudd, 2002). In the early years of operation, (Davy, 1983) estimated that the flux from a 2 m water cover would be 0.8 Bq/m^2/s, arguing on overall environmental and economic grounds for dry tailings to achieve a radon flux of 0.5 Bq/m^2/s. To date, there is no public data on the radon flux from water covers on the tailings facilities at Ranger.

Table 7. Radon fluxes and loads from abandoned, operating, rehabilitated and proposed waste rock, low grade and ore stockpiles

Project	Description	Period	$\%U_3O_8$	ha	Flux ($Bq/m^2/s$)	GBq/d	References
Rum Jungle	White's waste rock (12 points)	mid-1981	0.01	26.4	1.1	25	(Mason *et al*, 1982)
Rum Jungle	RJCS waste rock (36 points)	mid-1981	0.054	15	2.7	35	(Mason *et al*, 1982)
Rum Jungle	Proposed rehabilitation	mid-1980s	-	-	0.14	-	(Allen & Verhoeven, 1986)
Nabarlek	Ore stockpile (uncovered)	Oct 1979	1.86	2.9	130	326	(Leach *et al*, 1982)
Nabarlek	Ore stockpile (covered)	Nov 1979			38	95	(Leach *et al*, 1982)
Nabarlek	Waste rock (20 points)	mid-1981	0.013	-	0.26	-	(Mason *et al*, 1982)
Ranger	Waste rock (unspecified)	~1989	-	-	-	18.0	(Kvasnicka, 1990)
Ranger	Waste rock (unspecified)	1994-95 §	-	-	1.2 / 0.47 §	-	(Kvasnicka & Auty, 1996)
Ranger	Waste rock (unspecified)	Sept 1996	-	-	0.519	-	(Todd, 1998)
Ranger	Waste rock (very LGO)	mid-1998	~0.04	-	1.8	-	(ERA, 1999)
Ranger	Waste rock – trial 1 m cover	mid-1998	~0.04	-	<1 (0.88) #		(ERA, 1999)
Ranger	Tailings dam wall (very LGO)	mid-1981	0.010	-	0.21	-	(Mason *et al*, 1982)
Ranger	Waste rock (trial rehabilitation)	July 2002	-	-	0.937 ± 0.449	-	(Akber *et al*, 2004)
Ranger	Waste rock (pad area)	July 2002	-	-	0.526 ± 0.459	-	(Akber *et al*, 2004)
Ranger	Ore stockpile 7 (rock pile)	July 2002	-	-	1.686 ± 1.641	-	(Akber *et al*, 2004)
Ranger	Ore stockpile 7 (rim)	July 2002	-	-	0.950 ± 0.977	-	(Akber *et al*, 2004)
Ranger	Ore stockpile 7 (pad area)	July 2002	-	-	3.141 ± 1.949	-	(Akber *et al*, 2004)
Ranger	Ore stockpile 2 (rim)	July 2002	-	-	12.33 ± 17.08	-	(Akber *et al*, 2004)
Ranger	Ore stockpile 2 (pad area)	July 2002	-	-	15.68 ± 22.55	-	(Akber *et al*, 2004)
Ranger	Laterite stockpile (rim)	August 2002	-	-	38.40 ± 18.57	-	(Akber *et al*, 2004)
Ranger	Laterite stockpile (push zone)	August 2002	-	-	80.59 ± 40.84	-	(Akber *et al*, 2004)
Ranger	Laterite stockpile (pad area)	August 2002	-	-	5.158 ± 2.770	-	(Akber *et al*, 2004)
Coro. Hill	Areas adjacent to open cut	mid-1980s	-	-	0.18 ± 0.28	-	(DM, 1988)
Coro. Hill	Nearby regional baseline	mid-1980s	-	-	0.062 ± 0.007	-	(DM, 1988)
Koongarra	Ore stockpile (proposed)	1978 EIS est	-	-	70-184	-	(Noranda, 1978)
Koongarra	Waste rock stockpile (prop.)	1978 EIS est	-	-	9-26	-	(Noranda, 1978)
Yeelirrie	Waste rock (proposed)	1978 EIS est	-	418	~1.6	566	(WMC, 1978b)
Yeelirrie	Waste rock post-mining (pro.)	1978 EIS est	-	418	~0.9	339	(WMC, 1978b)
Yeelirrie	Waste rock (trial mining)	Nov 1976	0.44	small	0.0015	-	(WMC, 1979)
Yeelirrie	Waste rock (proposed)	1979 EIS est	-	418	2.82	975	(WMC, 1979)
O. Dam	Ore stockpile (proposed)	1982 EIS est	~0.08	-	-	8.6	(Kinhill, 1982)
Ben Lomond	Overburden (proposed)	1979 EIS est	0.0008	-	-	0.7	(Minatome, 1979)
Ben Lomond	Waste rock (proposed)	1979 EIS est	0.0033	13.6	-	3.6	(Minatome, 1979)
Ben Lomond	Ore stockpile (proposed)	1979 EIS est	-	-	-	1.2	(Minatome, 1979)
Ben Lomond	Waste rock (proposed)	1983 EIS est	-	10	0.5	4.4	(Minatome, 1983)
Ben Lomond	Low grade ore (proposed)	1983 EIS est	-	5	4	17.2	(Minatome, 1983)
Ben Lomond	Ore stockpile (proposed)	1983 EIS est	-	1	10	8.6	(Minatome, 1983)

§ Based on research over the 1994 dry and early 1995 wet seasons, with the lower wet season flux due to moisture in the waste rock; # Actual field results for the cover are not presented, only stating the average was "below" the 1 $Bq/m^2/s$ target, calculations suggested 0.88 $Bq/m^2/s$ (pp 140).



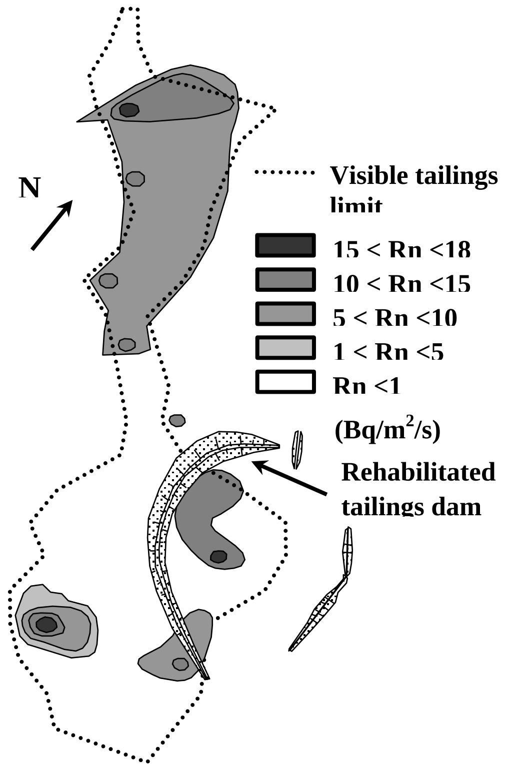


Figure 3 Radon emanation contours for uranium mill tailings at Rockhole (*left*) and Moline (*right*), June 1982 – Before rehabilitation (Bastias, 1987)

Table 8. Radon loads from abandoned, operating and proposed uranium mills

Project	Scale/Status	Description / Date of Survey	GBq/d	%U_3O_8	t U_3O_8/yr	References
Ranger	Comm/Op	1974 & 1975 EIS Estimates	44	0.3	3,000	(RUM, 1974, 1975)
Ranger	Comm/Op	1977 Ranger Inquiry Estimate	20→148	0.3	3,000	(Fox *et al*, 1977)
Ranger	Comm/Op	1989 & 1992 Research Estimates	147	0.3	3,000	(Kvasnicka, 1990, 1992)
Ranger	Comm/Op	1993 Research Estimates	150	0.3	3,000	(Akber *et al*, 1993)
Beverley [ISL]	Comm/Op	1998 EIS Estimate	~101	~0.18	~1,180	(Sonter, 1998)
Honeymoon [ISL]	Comm/Pr	2000 EIS Estimate	484	~0.12	~1,000	(SCRA, 2000)
Olympic Dam	Comm/Op	1982 EIS Estimate	16.4 [§]	~0.08	3,000	(Kinhill, 1982)
Olympic Dam	Comm/Op	June 1992→May 1993	57 [#]	0.083	1,351	(Davey, 1994)
Ben Lomond	Comm/Pr	1979 EIS Estimate				(Minatome, 1979)
Yeelirrie	Pilot/CM	1978 EIS Estimate	0.19		~12	(WMC, 1978a)
Yeelirrie	Comm/Pr	1978 EIS Estimate	311			(WMC, 1978b)
Koongarra	Comm/Pr	1978 EIS Estimate	46 [§]			(Noranda, 1978)

Comm Commercial; Op Operating (at present); Pr Proposed; Pilot Pilot mill; CM Care and maintenance; [§] Includes evaporation ponds; [#] Assumes all radon is released during grinding and leaching.

Table 9. Radon loads from abandoned, operating, rehabilitated and proposed uranium mill tailings piles

Project	Description	Date of Survey	ha	Flux (Bq/m^2/s)	GBq/d	References
R. Jungle [#]	Unrehabilitated surficial tails	late 1970s	~35	2.1	64	(Davy *et al*, 1978; Ritchie, 1985)
R. Jungle	Proposed rehabilitation target	-	-	0.14	-	(Allen & Verhoeven, 1986)
Nabarlek	Unrehabilitated dry tails (lab)	1980s	-	32.2	139	(Kvasnicka, 1986)
Nabarlek	Final in-pit tailings (pre-dicted)	1988 & 96	-	3.63 / 4.71	-	(Martin *et al*, 2002)
Nabarlek	UNSCEAR (93) advised data	-	5	2.1	9.1	(UNSCEAR, 1993)
Nabarlek	Rehabilitated tails – predicted	-	-	~10^{-22}	-	(Storm & Patterson, 1999b)
Nabarlek	Rehabilitated tails – actual	August 1996	5	4.710	20.3	(Kvasnicka, 1996)
Nabarlek	Rehabilitated tails – actual	Aug-Sep 99	5	<0.1→0.97→2.43	4.2	(Bollhöffer *et al*, 2003)
Nabarlek	Rehabilitated – exposed [1]	Oct. 2002	0.4	1.84→6.51→25.4	2.25	(Bollhöffer *et al*, 2003)
Rockhole	Unrehabilitated surficial tails	June 1982	~2	<5→~6→21.1	10.4	(Bastias, 1987)
Moline	Unrehabilitated surficial tails	June 1982	~18	<1→~2→17.9	31	(Bastias, 1987)
Jabiluka	Laboratory tailings – dry [2]	Early 1980s	-	21	-	(Strong & Levins, 1982)
Jabiluka	Laboratory tailings – moist [2]	Early 1980s	-	78	-	(Strong & Levins, 1982)
Jabiluka	Laboratory tails – saturated [2]	Early 1980s	-	0.74	-	(Strong & Levins, 1982)
Ranger	Ranger EIS Supplement #2	1975	-	<0.005	<0.37	(RUM, 1975)
Ranger	Ranger Inquiry – 2 m water	1977	-	~0.08	7.4	(Fox *et al*, 1977)
Ranger	Ranger Inquiry – moist	1977	-	0.16-1.6	14-144	(Fox *et al*, 1977)
Ranger	Ranger Inquiry – moist	1977	-	49.4	4,440	(Fox *et al*, 1977)
Ranger	Tailings prediction – moist	1981	-	44.4	3,990	(Haylen, 1981)
Ranger	Tails prediction – 2 m water	1983	-	0.8	72	(Davy, 1983)
Ranger	Tailings prediction – moist	1983	-	0.8-3.2	72-288	(Davy, 1983)
Ranger	Tailings prediction – dry	1983	-	0.5	45	(Davy, 1983)
Ranger	Unrehabilitated dry tails (lab)	mid-1980s	-	10.4	-	(Kvasnicka, 1986)
Ranger	Exposed tails beaches – moist	1989	-	2.6	96.2	(Kvasnicka, 1990)
Ranger	Advised data	mid-1990s	-	'0'	'0'	(Chambers *et al*, 1998)
Koongarra	Proposed operating tails	1978 EIS est			260	(Noranda, 1978)
B. Lomond	Proposed operating tails	1979 EIS est	6.8	24.5 [§]	144.1	(Minatome, 1979)
B. Lomond	Proposed operating tails	1983 EIS est	24	0.3	6.2	(Minatome, 1983)
Port Pirie	Unrehabilitated tails dam	1979-80	17.1 [†]	1.9 (average)	27.8	(AAEC, 1980)
Port Pirie	Unrehabilitated tails dam	1979-80	4.5 [‡]	1.5→5.6→7.4	19.2	(AAEC, 1980)
Port Pirie	Rehabilitated tails dam	1980-81	17.1	0.12 (average)	1.8	(Spehr, 1984; Crouch *et al*, 1988)
O. Dam	Proposed operating tails	1982 EIS est	400	0.6	207	(Kinhill, 1982)
O. Dam	Proposed rehabilitated tails	1982 EIS est	400	1	346	(Kinhill, 1982)
O. Dam	Operating tails	Aug 88-May 90	190	1.3 [3]	213	(IAEA, 1992)
O. Dam	Operating tails	mid 1990s	190	1.27 ± 1.57	208	(Kinhill, 1997)
O. Dam	Operating tails – uncracked	~1996-97	-	0.23	-	(Storm *et al*, 1997)
O. Dam	Operating tails – cracked	~1996-97	-	2.1	-	(Storm *et al*, 1997)
O. Dam	Operating tails	Jun 97-Mar 98	380	1.24→3.5→8.2	1,150	(Storm, 1998)
O. Dam	Trial cover (1 m clayey soil)	March 98	0.02	0.88	-	(Storm & Patterson, 1999a)
Lake Way	Proposed rehabilitated tails	1981 EIS est	-	0.75	-	(BLA, 1981)
Yeelirrie	Proposed operating tails [4]	1978 EIS est	330	~2.0	586	(WMC, 1978b)
Yeelirrie	Proposed rehabilitated tails	1978 EIS est	330	~11.4	3,261	(WMC, 1978b)
Yeelirrie	Proposed operating tails	1979 EIS est	330	~38.5	10,980	(WMC, 1979)

[#] 24 sampling points, ^{226}Ra 26.5 Bq/g (see also (Davy, 1983); [§] ^{226}Ra 17.15 Bq/g; [†] Total tailings area; [‡] Cells 2 & 3 only (majority of tailings); [1] Known as 'Unit 7', exposed pond sediments due to erosion, ^{226}Ra 15.4 Bq/g; [2] ^{226}Ra 52.4 Bq/g; [3] Moisture content 19%; [4] Includes pit dewatering.

Based on laboratory column studies, (Rogers & Nielson, 1981) argued that the water covers on mill tailings facilities were a major radon source, and presented a model to estimate such loads. Using this model (Diehl, 2004a) and Ranger's 1996 tailings pattern, a flux of 3.42 Bq/m^2/s can be calculated.

Of interest at Olympic Dam is the effect of shrinkage cracks on radon flux, with a study given by (Storm *et al*, 1997). Based on their data, cracks can significantly increase the radon flux, and though the full extent remains unclear, it could be as high as an order of magnitude.

It can be seen in Table 9 that both predicted and measured radon fluxes vary considerably. The direct comparison of much of this data is hampered by the different field measurement techniques and lack of full reporting (or measurement) of data relevant to quantifying radon behaviour. There is continuing management issues at many tailings sites, including Rum Jungle, Nabarlek, Mary Kathleen and others. In order to improve the prospects for future tailings management, a more coherent picture and quantitative framework is clearly required based on well defined and reported field-measured data.

3.10 *Radium-Contaminated Areas*

The deposition and accumulation of radium can lead to elevated activities which can, in turn, cause elevated radon fluxes. The "Magela Land Application Area" at the Ranger Project is one such area, and now exhibits a radon flux of 0.112 Bq/m^2/s (Akber *et al*, 2004). This is 60% higher than adjacent baseline measurements. Another site of extensive radium contamination is downstream of Rum Jungle. There are also radium-contaminated sites in South Australia and New South Wales from the processing of uranium ore for radium in the early 1900s, and though they are very small in scale, they did present a notable residential health issue (Mudd, 2004b).

3.11 *Total Project Radon Releases*

The total radon loads released by uranium projects across Australia is generally poorly understood with respect to changes from pre-mining or baseline conditions and relative to production levels. This is also complicated by the fact that the largest producer of tailings, Olympic Dam, produces uranium as a co-product with copper, gold and silver. The only realistic site for total load estimates is Ranger, for which a preliminary compilation is given in Table 10.

The UNSCEAR analyses (and others critiquing them) have only assumed radon is released in the long-term from mill tailings. This fails to account for what is often the biggest source by mass and area – waste rock, as well as other components which can sometimes provide significant radon loads, such as mills and abandoned mines. From an environmental (and radiological) perspective, it is the long-term success of rehabilitation and the cumulative changes from baseline which should be used as the basis for standards and assessing the local and global radiological consequences of uranium projects.

At current uranium projects, radon progeny are monitored in the surrounding environment, public radiological doses are estimated and provided these meet the relevant statutory requirements, no further work has been considered necessary. This approach is inadequate, however, when setting rehabilitation standards and estimating long-term global doses as the loads are needed relative to uranium production.

4 DISCUSSION

There are two major difficulties with estimating total radon loads from Australian uranium projects : (i) the lack of comprehensive data over time; and (ii) differing methods and focus giving rise to inconsistent measurements and reporting. Aspects of these problems include either no measured or reported radium activity, moisture content, density or porosity. It is likely that this could also explain, at least partly, some of the data variability within the tables.

It is noted by (Bollhöffer *et al*, 2003), in discussing the different radon flux values at the rehabilitated Nabarlek site, that discrepancies in measurement techniques and sample locations can affect overall results. Another issue is the geology and mining conditions for each deposit. A major issue with almost all studies is the lack of consistency on moisture data. Given its critical importance and climatic differences, this remains a vexed issue.

Table 10. Radon load estimates over time for the Ranger uranium project (GBq/d) (Mudd, 2004c)

Year	Tailings management	Mill	Ore SP	Waste rock SP	Mine pits	Tailings	Total
Pre-mine	-	0	0	0	372	5 †	377
1975	>2 m water cover	44	19 ‡	-	32	<0.37	96
1977	-	20-148	~96 ‡	-	20-281	14-144	150-669
1981	-	-	-	-	-	3,990	-
1980s	sub-aqueous deposition	-	-	-	-	197	-
1989	sub-aqueous & aerial deposition	147	318	18	34	148	665
1992	-	147	318	8	44	96	613
1993	sub-aerial deposition	150	325	15	26	94	610
1990s	sub-aqueous & aerial deposition	-	-	-	-	77	-

† Assuming a pre-mining flux of 0.05 Bq/m^2/s; ‡ Includes waste rock. SP Stockpiles.

Overall, this makes the comparison and use of the data somewhat problematical. Therefore, the detailed data compiled within this paper should be taken as indicative only. It should be emphasized, however, that an assessment or calculation of radon loads from a proposed uranium project should include accurate field data for all components (ie. more than just tailings) and not simply assume data or other properties.

It can be noted in the tables that for some older sites, both rehabilitated and abandoned (eg. Nabarlek), there is evidence of ongoing erosion problems leading to locally elevated radon fluxes. Although measurements may be taken at a point in time, it is important to continually monitor and assess the radon sources of all uranium project sites.

In comparison to the UNSCEAR data, it would appear that Australia's normalised radon and tailings data is similar in dry density at 1.6 t/m^3 but covers 1.2 ha/ GWe.year. To produce the 250 t U_3O_8 for 1 GWe.year requires about 162,400 t of 0.154% U_3O_8 ore, giving a normalised tailings thickness of 8.5 m. Depending on properties and conditions, fluxes from 3.3 to 18.9 Bq/m^2/s can be predicted [1]. Given the widely varying conditions and known data, however, a standardised rate is not considered realistic; instead, site-specific and comprehensive field studies should be used.

5 CONCLUSIONS

The extensive data for radon releases from Australian uranium projects has been systematically compiled and presented – arguably for the first time.

For the Nabarlek site, there is clear evidence that the use of modern environmental and radiological practices has led to a rehabilitated site which has lower overall radon loads being released. This is perhaps an unacknowledged benefit, although this has to be considered in the context of numerous other issues – social and economic impacts, ongoing water quality risks, weeds, erosion, and the like. For other sites, such as Ranger and Olympic Dam, it is possible that some lasting increase in radon loads will occur, even after rehabilitation. This is largely a result of both the scale and nature of the disturbance at each site, especially Olympic Dam where there was no radon expression prior to mining.

The UNSCEAR data and assumptions appear at best more realistic for Australian conditions than argued by some researchers, however, there is still more data needed to make an accurate assessment.

Overall, radon fluxes and loads still remain relatively underquantified given their importance in assessing local and global doses.

[1] Emanation coefficient 0.2, porosity 0.43, saturated moisture content of 21.2% (M_{water}/M_{total}); see (Diehl, 2004b).

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