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Radon releases from Australian uranium mining and milling projects: assessing the UNSCEAR approach

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Abstract

The release of radon gas and progeny from the mining and milling of uranium-bearing ores has long been recognised as a potential radiological health hazard. The standards for exposure to radon and progeny have decreased over time as the understanding of their health risk has improved. In recent years there has been debate on the long-term releases (10,000 years) of radon from uranium mining and milling sites, focusing on abandoned, operational and rehabilitated sites. The primary purpose has been estimates of the radiation exposure of both local and global populations. Although there has been an increasing number of radon release studies over recent years in the USA, Australia, Canada and elsewhere, a systematic evaluation of this work has yet to be published in the international literature. This paper presents a detailed compilation and analysis of Australian studies. In order to quantify radon sources, a review of data on uranium mining and milling wastes in Australia, as they influence radon releases, is presented. An extensive compilation of the available radon release data is then assembled for the various projects, including a comparison to predictions of radon behaviour where available. An analysis of cumulative radon releases is then developed and compared to the UNSCEAR approach. The implications for the various assessments of long-term releases of radon are discussed, including aspects such as the need for ongoing monitoring of rehabilitation at uranium mining and milling sites and life-cycle accounting.

Keywords: Uranium mining; Radon; Australia; UNSCEAR

1. Introduction

The exhalation and release of radon gas into the environment are the products of the radioactive decay chain of primordial uranium or thorium, specifically the isotopes ^{238}U, ^{235}U and ^{232}Th. The radon isotopes formed from these decay chains are ^{222}Rn ('radon'), ^{219}Rn ('actinon') and ^{220}Rn ('thoron'), which are the direct decay products of the radium isotopes ^{226}Ra, ^{223}Ra and ^{224}Ra, respectively, in these chains. Due to the low abundance of ^{235}U in natural uranium and the short half-life of actinon (4 s), most work concentrates on ^{222}Rn and its decay progeny since this is the dominant source of exposure. In general, most uranium deposits contain low primary thorium (^{232}Th) and hence thoron (^{220}Rn) is generally considered to be of minor radiological importance. All reference to radon and radium hereafter refers to ^{222}Rn and ^{226}Ra, respectively.

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Radon is a chemically inert noble gas with a half-life of about 3.8 days, while its decay products or progeny of various isotopes of bismuth (Bi), polonium (Po) and lead (Pb) generally forms solids at normal environmental conditions (Cothern and Smith, 1987). The half-lives of radon progeny vary from microseconds to minutes to years. The rates of radon release are complex and depend on many factors, such as rock mineralogy and structure, the distribution of parent radionuclides (e.g. ^{238}U, and ^{226}Ra), temperature and moisture content (Barretto, 1973; Cothern and Smith, 1987; Hart, 1986; Lawrence, 2006). The fraction of radon which is released relative to its total production is known as the emanation coefficient, and can range from 0 to 1 but is generally between 0.2 and 0.5 (Flügge and Zimens, 1939).

Due to the natural abundance of about 2.7 mg/kg uranium in soils and rocks (Langmuir, 1997; Titayeva, 1994), there is a global average radon exhalation from soils of about 0.015−0.023 Bq/m^2/s (UNSCEAR, 1982). The seasonally-adjusted arithmetic mean radon and thoron exhalation from Australian soils are about 0.022 ± 0.005 and 1.7 ± 0.4 Bq/m^2/s, respectively (Schery et al., 1989). The average ^{226}Ra and ^{224}Ra soil activities are 28 and 35 mBq/g, respectively (Schery et al., 1989).

Within the vicinity of a uranium deposit or project, the release rates of radon and activities in air can be elevated over natural background, depending on local conditions and/or project operations. The inhalation or ingestion of significant activities of radon and progeny has long been considered to be related to elevated incidences of lung cancer and other diseases in uranium industry workers (Dalton, 1991; Fry, 1975; NAS, 1980; NAS, 1988; Teleky, 1937).

In recent years there have been some attempts to quantify the long-term (~10,000 years) public radiological exposure from the release of radon due to uranium mining and milling operations as part of life-cycle analyses of the nuclear fuel chain. The principal work has been undertaken by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in their periodic reports to the United Nations General Assembly. The main analysis of radon releases and the associated public radiological exposure over 10,000 years are given in UNSCEAR (1993), with a minor update by UNSCEAR (2000). The UNSCEAR analyses combine other stages of the nuclear fuel chain and present normalised radiological exposures per annual unit of energy generated, summarised in Table 1. The different estimates from the 1993 and 2000 reports are based on criticisms, feedback and the adoption of scenarios perceived to be more realistic for modern uranium mines. Both UNSCEAR estimates suggest that uranium mining and milling, based on the assumption of radon releases from tailings only, are the major factors in long-term public radiation exposure from the nuclear fuel chain, generally comprising between 16% and 75% of the local and global exposures from the nuclear fuel chain. The UNSCEAR (1993) estimate for global exposure

Table 1
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 year)					
UNSCEAR report	1993	2000	2000	2000	2000	2000
Period		1970−1979	1980−1984	1985−1989	1990−1994	1995−1997
Local and regional component						
Mining, milling and 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	5×10^{-5}	5×10^{-5}	5×10^{-5}	5×10^{-5}	5×10^{-5}	5×10^{-5}
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: UNSCEAR (1993, Table 53, p. 200) and UNSCEAR (2000, Table 45, p. 284).

from tailings-derived radon was 150 person Sv/GWe year (ranging from 1 to 1000), with the UNSCEAR (2000) estimate being 7.5 person Sv/GWe year.

The radon data and assumptions used by UNSCEAR in their analyses have been questioned by Chambers et al. (1998a,b) and Frost (2000). In general, these authors argue 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. (1998a,b) argue that the long-term radiological exposure due to radon is 0.96 person Sv/GWe year, considerably lower than the UNSCEAR estimates.

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

It is the normal standard of radiation dose management to follow the ‘as low as reasonably achievable’ or ALARA principle. That is, radiation exposure and doses should be kept to the minimum practicable. In the context of life-cycle analyses of the nuclear fuel chain, and uranium mining specifically, this therefore means the minimisation of public doses during operation and to ensure any changes from baseline radiological conditions following rehabilitation are also minimal, or even potentially beneficial (i.e. a reduction).

For this paper, radon exhalation shall refer to the radon per unit area per time ($Bq/m^2/s$) that enters the environment while radon releases shall be used to specify the mass per time (GBq/d) at which radon enters the environment.

The sources of radon from a typical uranium project are now reviewed followed by a detailed review of radon releases from the various Australian projects compared to pre-mining, where known. The comprehensive data set is then analysed to provide a more systematic basis for the figures used to assess the long-term radiological exposure due to radon as per the UNSCEAR approach. The implications for current uranium projects in Australia are then discussed.

2. Radon source terms

The principal sources of radon at a uranium mining and milling project are uranium ore (including low-grade ore), waste rock, open cuts or underground mines, processing mill, water management ponds and tailings. Sites where contamination has occurred, primarily due to radium, can also be a source of radon. For an *in situ* leach mining site, the dominant radon sources are the processing mill, groundwater bores, solution pipelines and water management ponds. Assuming a project site is effectively rehabilitated, the only change to radon releases is the removal of the mill as a major source and the long-term success of rehabilitation works on tailings, remaining ore, waste rock and contaminated areas. Any analysis of radon releases should therefore assess all of these sources and not just focus on tailings.

The main properties required to quantify radon releases include specific radium activity, material porosity and density, moisture content, and the variation of the emanation coefficient and the radon diffusion coefficient with moisture content. Based on experiments, the radon diffusion coefficient can be calculated from theoretical considerations providing that other variables are known, such as moisture content and porosity (Hart, 1986; Rogers and Nielson, 1981; Strong and Levins, 1982). An alternative approach and model are developed by Rogers and Nielson (1981) using moisture content and pore size distribution to predict radon diffusion rates and overall exhalation.

The United States Nuclear Regulatory Commission estimated the radon source terms for a ‘model mill’ in the Final Generic Environmental Impact Statement on Uranium Milling (USNRC, 1980). The ‘model mill’ processed 0.56 Mt ore per year grading 0.10% U_3O_8 to produce 520 t U_3O_8, it had an ore pad area of 0.5 ha, with a tailings dam area of 50 ha and a dry density of 1.6 t/m^3 (Table 5-1, pp. 4–5). The analyses suggested that ore stockpiles and crushing facilities would release 6.9 GBq/d of radon, while tailings would release about 446 GBq/d, including a small allowance for dispersed ore and tailings of 4.9 GBq/d (Table 5-5, pp. 5–8).

In Australia, the Ranger Uranium Environmental Inquiry (1975–1977) considered that the main source of radon releases from the Ranger project would be 20–148 GBq/d from the processing mill, about 96 GBq/d from ore stockpiles, between 20 and 281 GBq/d from the open pits and 1.4–14 GBq/d from saturated or water-covered tailings (Fox et al., 1977). The most controversial aspect of radon releases was tailings. Radon data presented to the Inquiry and more recent estimates have ranged from ‘0’ to 4440 GBq/d (Mudd, 2002). There are no published systematic measurements from the Ranger project of all radon sources in one study to verify the Ranger Inquiry predictions.

The exhalation and release of radon from different uranium deposits will vary considerably, depending on local geologic structure and environmental conditions. An important principle in the assessment of radon impacts due to uranium mining and milling is the change from existing baseline conditions governed by the above, especially given the altered nature of the properties of mined materials compared to *in situ* geology. It is only in more recent decades, however, that pre-mining studies have been undertaken in Australia, although not necessarily as comprehensively as needed for long-term impact assessment.

3. Uranium mining and milling wastes in Australia

3.1. Overview

The mining, milling and export of uranium have been undertaken on a large scale in Australia since 1954 and have gradually expanded to a current annual production of about 11,000 t of uranium oxide (U_3O_8). Small but determined attempts to develop a radium mining industry between 1906 and 1934 failed to lead to commercial uranium production (Mudd, 2005). Most modern uranium mines have been open cut, although some have been underground plus some *in situ* leach or 'solution' mining sites. The currently operating commercial mines are Ranger (open cut), Olympic Dam (underground) and Beverley (acid *in situ* leaching). To date, there has been a total of 11 uranium mills, including pilot projects, and about 31 mines of various scale supplying ore to adjacent or nearby mills or for pilot milling and exploration work. The location of uranium mining and milling sites and other uranium deposits in Australia is shown in Fig. 1, with annual production from 1954 to 2005 in Fig. 2. The quantity of uranium production, ore grades and associated mine wastes is given in Table 2. A compilation of pertinent data for uranium deposits referred to in this paper is given in Table 3.

The management of uranium mill tailings and mine wastes in Australia has changed over the years as regulation of the radiological and environmental hazards has improved and community expectations evolve. During the 1950s in the Northern Territory, tailings and liquid wastes were generally discharged onto adjacent lowland areas which formed part of creek lines and rivers. During the intense rainfall of the tropical wet season, both erosion and water quality impacts were quite significant. In contrast, the mills in arid regions of Queensland and South Australia constructed engineered dams to retain tailings and liquid wastes. From the 1970s it has been a standard regulatory and community preference to use above ground dams for interim management only and to transfer tailings back into a mined out pit as soon as practicable after the completion of mining. Although *in situ* leach mining was tested on a pilot scale in the 1980s using acid leaching at Honeymoon and alkaline leaching at Manyingee, acid leaching has only recently been developed on a commercial scale at Beverley in 2001.

The management of low-grade ore and waste rock has received less attention despite being potentially significant radon sources. In general, these materials have been placed in piles or heaps. At some sites, due to acid mine drainage, the heaps have been rehabilitated with soil covers while at other sites they have or will be covered mainly for erosion and water quality control.

There are very few measurements of radon releases from processing mills in Australia as well as from contaminated areas, water management ponds and active mines (open cut and underground).

3.2. Average tailings data

The data in Table 2 show that the production of each tonne of Australian uranium (as U_3O_8) requires about 848 t of ore and 1152 t of combined low-grade ore and waste rock. The average ore grade is about 0.146% U_3O_8 (range 0.075% to ∼2% U_3O_8) with a specific radium activity of 15.2 Bq/g (range 0.56−191 Bq/g; assuming secular equilibrium and minimal radium losses during milling and storage), while the tailings contain residual uranium of about 0.028% U_3O_8 (range 0.02% to ∼0.10% 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 exhalation into the environment than a thinner but greater area tailings pile. A compilation of the areas and dry densities of the different tailings' piles in Australia are given in Table 4, based on existing, proposed or as-rehabilitated scenarios. The tailings data for Rum Jungle are approximate only (due to conflicting sources).

UNSCEAR adopted a tailings dry density of 1.6 t/m^3. In practice, most tailings Australian sites have a density lower than this, such as the above ground dam at Ranger with a density of about 1.0 t/m^3 (Li et al., 2001; Sheng

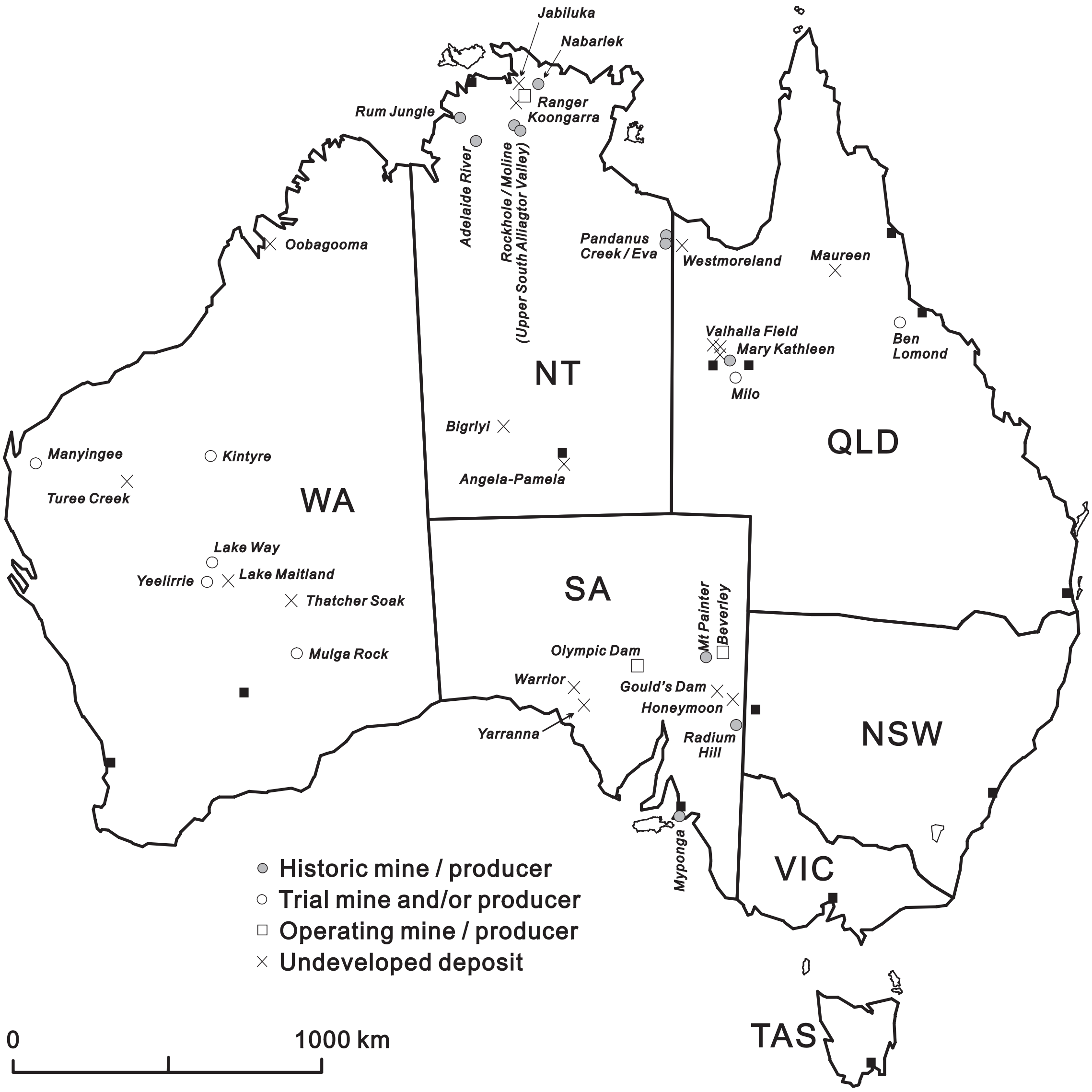

Fig. 1. Location of major uranium deposits in Australia.

et al., 1997) and Pit 1 tailings facility averaging about 1.4 t/m^3 (2005 Edition, ERA, 1984–2005). For Ranger, the tailings particle density is approximately 2.7–2.8 t/m^3 (Sheng et al., 2000; Sinclair, 2004). The Olympic Dam tailings' dams, however, apparently achieve a higher density ranging from 1.6 to 2.0 t/m^3 and averaging 1.7–1.8 t/m^3 with tailings particle density ranging from 3.2 to 3.6 t/m^3 (Johnston, 1990; Ring et al., 1998; Waggitt, 1994). The initial tailings density at Nabarlek in the early 1980s was not more than 1.0 t/m^3 (OSS, 1983) but by the time of complete site rehabilitation in 1994, a density of about 1.3 t/m^3 can be estimated based on pit volume, milling rates, and final depths of tailings, waste rock and covers. There is a general lack of tailings density data at older sites, with some of the values in Table 4 either deduced or estimated.

To date, the 123 Mt of Australian uranium mill tailings are estimated to average the UNSCEAR density of 1.6 t/m^3 at a volume of about 78 Mm^3, and an average depth of the order of 14 m.

Based on the data in Table 4, currently proposed rehabilitation strategies and using the UNSCEAR figure of 250 t U_3O_8/GWe year, a normalised tailings production value of 0.95 ha/GWe year can be estimated – virtually the same as

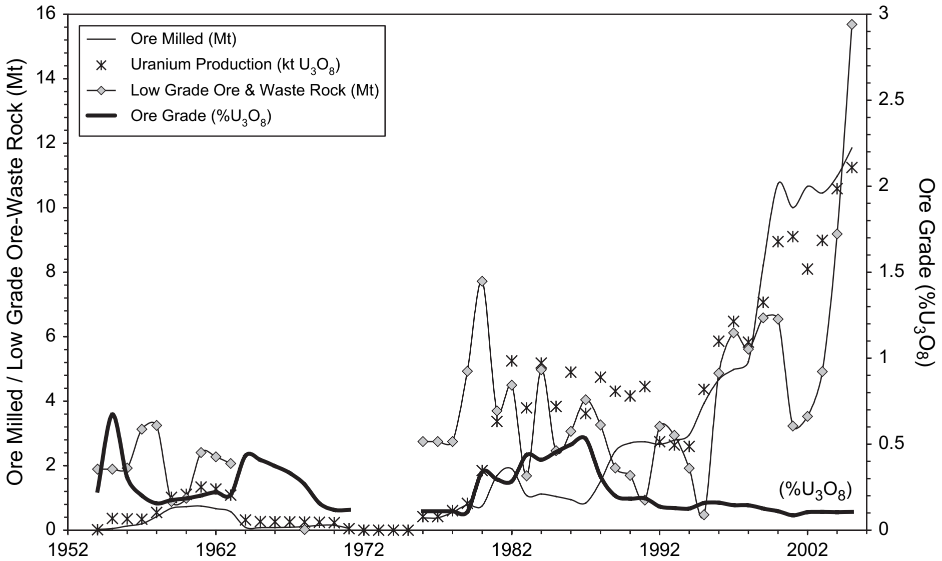

Fig. 2. Annual Australian uranium production statistics 1954–2005.

the UNSCEAR estimate of 1 ha/GWe year. Although rehabilitation works are planned for sites such as Ranger and Olympic Dam, the areal extent of the tailings repositories is difficult to predict given the potential for future expansion at Olympic Dam and evolving extensions to mine life at Ranger. These calculated values are therefore indicative only.

3.3. Average waste rock data

The total amount of waste rock, including low-grade ore, produced by uranium mining in Australia is quantified within a reasonable order of magnitude. Based on data in Table 2, about 175 Mt has been excavated to date (waste rock data for underground and most older mines are generally not available). The most significant sites for waste rock are Ranger, Mary Kathleen, Rum Jungle, Olympic Dam and Nabarlek. In the future, if the proposed expansion of Olympic Dam proceeds, this site alone may contain waste rock covering some 1600–4400 ha (depending on height, at 160 or 60 m, respectively) (BHPB, 2005).

The average uranium grades of the various waste rock piles are generally not available, though some data exist for Ranger, Nabarlek and Rum Jungle as compiled in Table 5. It can only be assumed that waste rock at other sites contains $<0.02\%$ U_3O_8. The quantity of waste rock is primarily due to Ranger and Mary Kathleen, and to a lesser extent by Rum Jungle and Olympic Dam.

Overall, the 1152 t of combined low-grade ore and waste rock produced per tonne of Australian uranium can be expected to have a grade between 0.01% and 0.03% U_3O_8. The average mass is about 519 kt/ha, and using a typical waste rock density of 2 t/m^3, this gives an expected height of about 26 m.

4. Estimated and measured radon exhalation and releases

The measurement of radon exhalation has only been undertaken in more recent decades, commensurate with improved understanding of radon management in uranium mining and milling. Many of the recent radon studies were undertaken as part of an Environmental Impact Statement (EIS) or to support technical aspects of a project's design (e.g. radiation protection for mine workers). There is still, however, a lack of comprehensive radon exhalation and release studies at most former and current uranium project sites in Australia. Most studies only report exhalation data and do not measure (or at least do not report) other important variables such as porosity, moisture content and measured or calculated radon diffusion coefficients, or the area and grade of the active radon source.

Table 2
Principal ore, tailings and waste data for Australian uranium mines and mills to December 2005 (Mudd, 2007)

	Operation	Ore milled (t)	Ore ($\%U_3O_8$)	Prod. ($t\ U_3O_8$)	Tailings ($\%U_3O_8$)	Tailings ^{226}Ra[a]	Low-grade ore and waste rock (t)	Other metals produced/ ores mined (±milled)[b]
Olympic Dam, SA	1988–2005[j]	85,396,312	0.075	41,234	~0.026[c]	7.65	~10,250,000	1957 kt Cu, 25.2 t Au, 253 t Ag
Ranger, NT	1981–2005[j]	30,772,000	0.310	85,121	0.033	32.1	~121,150,000	–
Nabarlek, NT	1980–1988	597,957	1.84	10,955	0.036	191.1	2,330,000	–
		157,000[d]	0.05–0.1		~0.02[i]	5.2		
Beverley, SA[e]	2001–2005[j]	~31,750 ML[f]	~0.18	4070	–	–	601 ML	–
	1998[h]	153 ML[h]		33.27[h]			2.686 ML[h]	
Honeymoon, SA[e]	1982[h]	(ISL[e])	~0.12	No data	–	–	41.2 ML	–
	1998–2000[h]			29.4[h]				
Mary Kathleen, QLD	1976–1982	~6,200,000	0.10	4801	~0.02	10.4	17,571,000	–
Small/pilot Mines	1970–1980	Various		≫12[h]	–	–	≫150,000[i]	–
Moline, NT	1956–1964	135,444	0.46	716.0	0.070	47.5	Unknown	152.6 kt CuAu and PbZnAg ore
Rockhole, NT	1959–1962	13,418	1.11	139.7	0.066	115.3	Unknown	–
Mary Kathleen, QLD	1958–1963	2,668,094	0.172	4091.8	~0.019	16.2	4,539,652	–
Radium Hill, SA	1952–1961	822,690	0.119	–	~0.02	0.52	Unknown	–
Port Pirie, SA	1955–1962	~153,400	~0.74	852.3	~0.10	76.8	Unknown	1500 t monazite
Rum Jungle, NT	1954–1971	1,496,641	0.35	3530	0.086	33.7	~18,027,000	2.6 Mt Cu ore/87 kt Pb ore
Small/pilot Mines[g]	1950s–1960s	9225[g]	0.92	–[g]	–[g]	~95.5	Unknown	–
Mt Painter, SA	1910–1934	~933	~2.1	~3 t[i]	–	–	Unknown	–
Radium Hill, SA	1906–1932	>2150	~1.4[i]	~7 t[i]	–	–	Unknown	–
Total		~128.4 Mt	0.146%	155,595	0.028%	15.2	~175 Mt	–

[a] ^{226}Ra in Bq/g based on measured data or assuming secular equilibrium and average ore grade.
[b] Such as base metal or other ores milled (e.g. copper at Moline, thorium/monazite at Port Pirie; though the Rum Jungle lead ore was not milled).
[c] Adjusted for coarse backfill and copper extraction (based on 94.6% of ore milled as tailings and assuming no uranium in coarse backfill).
[d] Low-grade ore experimentally heap leached.
[e] ISL involves chemical solutions only (in ML) and no physical extraction of ore.
[f] Includes some estimated data.
[g] Ore milled at Rum Jungle ('RJ'), not included in sub-totals.
[h] Pilot plant only.
[i] Data uncertain (approximate only).
[j] Still operating at end of 2005.

Table 3
Resources and dimensions of major uranium deposits in Australia (adapted from Mudd, 2007, and additional references)

Deposit	Resources			Approximate (or average) dimensions (m)				Additional references
	Ore (Mt)	(% U_3O_8)	(t U_3O_8)	Depth[a]	Length	Width	Thickness	
Honeymoon, SA	2.75	0.12	3300	100–120	1000	400	4.3	SCRA (2000)
Beverley, SA[b]	~10.4	0.18	~17,900	100–120	~4000	400–750	20–30	HR (1998)
Olympic Dam, SA[c]	3970	~0.04	~1,500,000	350	~5000	~400–2300	~400	Kinhill (1997)
Ben Lomond, QLD	2.98	0.23	6800	50–75	750	150	100	McKay and Miezitis (2001)
Ranger 1, NT[d]	19.78	0.321	63,500	1–20	500	300	~185	Kinhill and ERAES (1996), McKay and Miezitis (2001)
Ranger 3, NT[e]	53.0	0.16	~85,000	~20–30	900	500	~25–100	McKay and Miezitis (2001), Needham (1988)
Nabarlek, NT	0.76	1.84	10,955	2–5	230	10	85	Needham (1988)
Jabiluka 1, NT	1.36	0.25	3400	~25	350	225	Up to 35	Battey et al. (1987), McKay and Miezitis (2001)
Jabiluka 2, NT[f]	31.1	0.53	163,000	~80–120	1100	400	Up to 135	Battey et al. (1987), McKay and Miezitis (2001), Needham (1988)
Koongarra 1, NT	1.83	0.8	14,550	2–25	450	~30–100	100	Hegge et al. (1980), Needham (1988)
Koongarra 2, NT	0.77	0.3	2300	50–250	100	~30–100	Up to 200	Hegge et al. (1980)
Coronation Hill, NT	0.34	0.54	1850	~150	No data	No data	No data	McKay and Miezitis (2001)
Lake Way, WA	5.98	0.09	5200	2–10	~3000[g]	~2000[g]	1.5	McKay and Miezitis (2001)
Yeelirrie, WA	35.2	0.15	52,500	2–8	~9000[g]	Up to 1500[g]	3–4	McKay and Miezitis (2001)

[a] Average depth to start of economic mineralisation.
[b] Adjusted from resource prior to mining, after allowing for production of 3103 t U_3O_8.
[c] Resources at June 2005, excluding milled ore of 85.4 Mt at 2.62% Cu, 0.075% U_3O_8, 5.9 g/t Ag and 0.55 g/t Au.
[d] Completely mined and milled.
[e] Includes reserves and resources (December 2005) but not milled ore derived from Ranger 3 (~10.9 Mt at 0.20% U_3O_8).
[f] Mineralisation extends to depths of 600 m, possibly deeper (possible ore zone extensions are still untested to the east and south of the deposit).
[g] Mineralisation not continuous over this area.

The variation in the radon emanation coefficient with moisture content for Ranger and Jabiluka ores and laboratory tailings is shown in Fig. 3. Further studies on radon behaviour are given by Hart (1986), Lawrence (2006), Storm (1998), Strong and Levins (1982), and Todd (1998).

4.1. Pre-mining radon exhalation

The available pre-mining radon exhalation surveys are compiled in Tables 6 and 7. The pre-mining radon exhalation contours for the Koongarra and Yeelirrie deposits are shown in Figs. 4 and 5, respectively, with the pre-mining radon activity in soil at Nabarlek shown in Fig. 6. In general, it is only uranium deposits of sufficient size and which appear from a shallow depth that give rise to a significantly elevated radon exhalation at the surface (comparing Tables 3, 6 and 7). Some examples are the calcrete–carnotite deposits in Western Australia (Yeelirrie, Lake Way) and the unconformity deposits at Ranger and Nabarlek in the Northern Territory. Conversely, there is no significant mineralisation-related radon signature from Olympic Dam, Beverley, Jabiluka and others.

The use of radon techniques in uranium exploration has been performed in Australia, most notably at the Rum Jungle mineral field, NT (Stewart, 1968), at Yeelirrie, WA (Severne, 1978) and the Alligator Rivers Region, NT (Gingrich and Fisher, 1976), though it does not appear to have been widely adopted and is thus of limited use in the context of this paper.

4.2. Radon sources during open cut, underground, in situ leach mining

There are only scattered data on the exhalation and release of radon from either underground or open cut uranium mining (Table 8). The EIS estimates for some proposed mines are also included for comparison.

A detailed study of radon releases from underground uranium mines in the United States was given by Jackson et al. (1981), with further analyses by Hans et al. (1981). The dominant radon sources were ventilation shafts with

Table 4
Uranium mill tailings pile data for Australian projects to December 2005

Project	Tailings facility	Area (ha)	Mass[a]	Dry density	Volume	Depth	References
Radium Hill	No. 1 Dam	~8	~100,000 t	Unknown	Unknown	~ 2 m (?)	Hill (1986), Sheridan and
	No. 2 Dam	~32	723,000 t			~5 m (?)	Hosking (1960), Waggitt (1994)
Port Pirie	Surface dam	~30	151,550 t	Unknown	Unknown	~2 m (?)	Waggitt (1994), Wilkinson (1977)
Rum Jungle[b]	Surface deposition minus erosion[f]	34	~576,000 t	~1.7 t/m^3	~0.34 Mm^3	~1.0 m	DNT (1978), Kraatz (1998),
	In-pit (White's)	11	~600,000 t	~0.6 t/m^3 (?)	~1.0 Mm^3	No data	Kraatz and Applegate (1992)
	In-pit (Dyson's)	6	~500,000 t	~2.3 t/m^3 (?)	~0.22 Mm^3	No data	
Mary Kathleen	Surface dam	29	~8,900,000 t	~1.4 t/m^3 (?)	~6.4 Mm^3	~22 m (?)	MKU (1986), Ward (1985)
Rockhole[c]	Surface deposition minus erosion[f]	~2	~12,000 t	Unknown	Unknown	–	Waggitt (1994)
Moline[d]	Surface deposition minus erosion[f]	18	~202,000 t	~1.2 t/m^3	~0.188 Mm^3	~1.0 m	Bastias (1987), Waggitt (1994)
	Surface dam (as rehabilitated)	~6	~208,000 t	No data	No data	No data	
Nabarlek	In-pit (including heap leach wastes)	5	744,000 t	~1.3 t/m^3	~0.47 Mm^3	<65 m	Bailey (1989)
Ranger	Interim surface dam (to Pit #3)[e]	117	13,624,000 t	1.0 t/m^3	13.6 Mm^3	11.6 m	ERA (1984–2005), Li et al. (2001),
	In-pit (Pit #1)	51	~18,951,000 t	~1.38 t/m^3	~13.7 Mm^3	<150 m	Sheng et al. (2000), Sheng et al. (1997)
	In-pit (Pit #3)[e]	~75[e]	Not applicable	–	–	–	
Olympic Dam	Current surface dam	~750	~78,500,000 t	1.75 t/m^3	~45 Mm^3	~5.9 m	Mudd (2007)
	Proposed final dam	~1850	Up to ~4.1 Gt	–	–	<30 m	BHPB (2005)
Approximate total (Dec. 2005)		1046	123.01 Mt	~1.6 t/m^3	–	~14 m	

[a] Allows for extraction of uranium, base metals and removal of the coarse fraction where appropriate, though in general the reagents added during milling equals the mass removed (e.g. pyrolusite and acid).

[b] Data on tailings in the pits at Rum Jungle are very poor, data as used are approximate only. The surficial tailings were dumped in Dyson's open cut during rehabilitation.

[c] About half of the Rockhole tailings were removed and transported to Moline for reprocessing and emplacement in the mid 1980s.

[d] The Moline tailings were excavated, reprocessed for gold and emplaced in a new engineered dam in 1986–1987, including about 6000 t of tailings transported from Rockhole. Data include base metal tailings (due to mixing with uranium tailings). After this project, a medium-size gold project was undertaken during 1988–1992 (Moline Hill, see Anon., 1988; Miller, 1990), depositing some 2.3 Mt of gold tailings over the old uranium-base metal tailings.

[e] Expected quantity of tailings for Ranger's Pit #3, including the interim above ground dam, is of the order of 38 Mm^3 (depending on final mine plan but excluding Jabiluka).

[f] Removed during rehabilitation works.

Table 5
Waste rock data for selected Australian projects (Mudd, 2007)

Project	Deposit/mine	Low-grade ore[a]		Waste rock		Total area (ha)
		(Mt)	(% U_3O_8)	(Mt)	(% U_3O_8)	
Rum Jungle	White's	–	–	8.64	0.004	26.4
	Dyson's	0.0478	0.077	2.032	0.005	8.43
	Rum Jungle Creek South	0.116[b]	0.066	4.877	0.018	21.9
	Mt Burton	0.0035	0.072	0.254	–	3.28
	Mt Fitch	–	–	0.020	–	~0.5?
	Intermediate (Cu)	–	–	1.727	0.005	6.85
Nabarlek	Nabarlek	0.157	~0.05	2.33	0.013	6
Ranger	Ranger #1[c]	16.219	~0.075	22.338	<0.02	~200
	Ranger #3	>18.813	~0.070	>9.865	<0.02	
Olympic Dam	Olympic Dam	–	–	~10.25[d]	–	–
Mary Kathleen	Mary Kathleen (1956–1963)	0.566	–	3.864	–	64
	Mary Kathleen (total)	–	–	~22[e]	–	
Totals		>35.92	~0.072%	~81.832	~0.01%	~340

[a] Generally defined as >0.02% U_3O_8.
[b] Apparently processed at Rum Jungle between 1969 and 1971.
[c] Conflicting data exist – one estimate states that for Ranger #1 a total of 19.8 Mt of ore, 4.5 Mt of low-grade ore (~0.05–0.10% U_3O_8) and 55.5 Mt of waste rock and very low-grade ore (~0.02–0.05% U_3O_8) were mined (ERA, 1999).
[d] Waste rock is returned underground as backfill (though a small stockpile may exist at the surface in the short term).
[e] Total of low-grade ore and waste rock from 1956 to 1982.

only a minor contribution from waste and ore stockpiles, mine water and subtracting credit for background radon. Jackson et al. (1981) estimated a normalised radon release at 1088 GBq/t U_3O_8. An important aspect of these studies is the relationship demonstrated between radon releases and cumulative production, with older mines (higher total production) showing higher radon releases relative to younger mines.

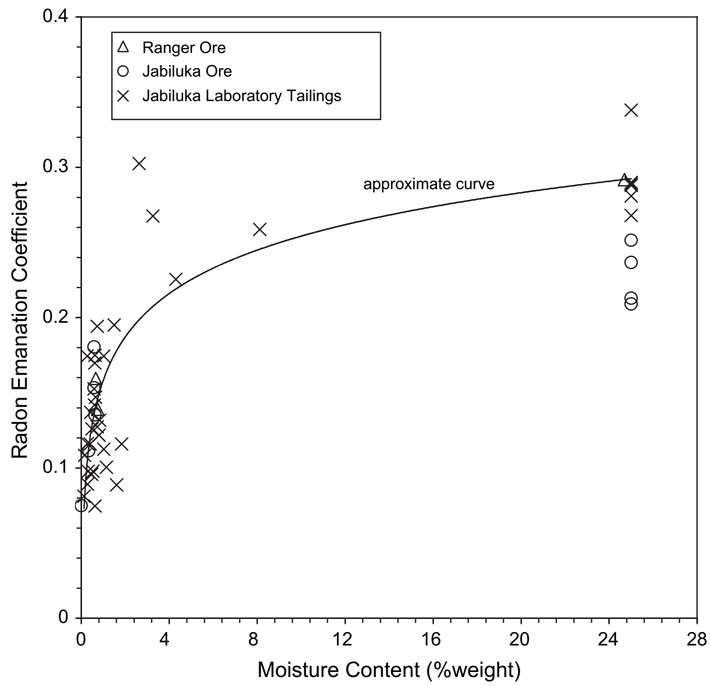

Fig. 3. Effect of moisture content on the emanation coefficient of Ranger ore and Jabiluka ore and laboratory tailings (Hart, 1986; Strong and Levins, 1982) (25% moisture assumed for saturated samples).

Table 6
Pre-mining and/or background radon exhalation and release surveys – Northern Territory

Location	Period or date of survey	Area (ha)	Exhalation ($Bq/m^2/s$)	Release (GBq/d)	References
Kakadu region – average[a]	Throughout 1998	–	0.030	–	Auty and du Preez (1994),
Kakadu region – range[a]	Various 1992–1998		0.009 → 0.057[b]		Todd (1998)
Kakadu–Magela Creek	August 2003 (31 samples)	–	0.21 ± 0.02	–	Lawrence (2006)
Kakadu–Mudginberri	April and Sept. 2003 (44 samples)		0.035 ± 0.02		
Kakadu–Mirray	March 2003 (45 samples)		0.039 ± 0.02		
Kakadu–Jabiru Water Tower	March and August 2003 (46 samples)		0.018 ± 0.01		
Kakadu–Jabiru East	August 2003 (45 samples)		0.043 ± 0.02		
Jabiluka 2[g]	Sept.–Dec. 1992	–	0.046	–	Auty and du Preez (1994)
Jabiluka Decline (east of #2)	Nov. 1992 and July–Aug. 1993		0.025		
Koongarra 1[g]	June 1978	12.53[c]	2.43[c]	26.1	Davy et al. (1978)
Koongarra 2[g]	June 1978	–	<0.05	–	Davy et al. (1978)
Nabarlek[g]	Sept. 1978	5	3.7 → 44.0[d]	–	Clark et al. (1981)
	June 1979		11.5 → 164.0[d,e]		
Nabarlek region	1999–2002	–	0.016 → 0.049	–	Bollhöffer et al. (2006)
			0.031 (average)		
Ranger 1[g]	~March 1978[f]	43[f]	3.8[f]	~141[f]	Haylen (1981)[f]
		91[f]	2.5[f]	~197[f]	
Ranger 1–3 region[g]	(Calculated estimate)	245	1.78	377	Kvasnicka and Auty (1994)
Ranger 1[g]		44	4.1	156	
Ranger 3[g]		66	2.5	143	
Area around 1 and 3		81	1.0	70	
Australian background	–	–	0.022 ± 0.005	–	Schery et al. (1989)

[a] Primarily in the near vicinity of the Ranger project area.
[b] Values >0.06 $Bq/m^2/s$ were detected above known as mineralisation (e.g. Ranger 2), ranging from 0.096 to 0.280 $Bq/m^2/s$ (three points excluded from average of 18 measurements).
[c] Average ^{222}Rn exhalation for 5.29, 3.69, 2.57, 0.79 0.13 and 0.063 ha is 0.57, 2.02, 4.07, 8.15, 13.18 and 20.76 $Bq/m^2/s$, respectively.
[d] Range given as minimum and maximum values only (no average).
[e] Vegetation cleared in preparation for mining.
[f] The AAEC report on this Ranger radon survey was apparently never completed. The data quoted are cited by Haylen (1981, p. 100) (Haylen worked for the AAEC in the late 1970s as a geologist). Further reference to this AAEC study is made in radon studies at Koongarra (Davy et al., 1978, p. 5), broader radiation studies at Nabarlek (Clark et al., 1981, p. 24; Davy, 1978, p. 78), as well as Yeelirrie, WA (Brownscombe and Davy, 1978, p. 14) while NTDME (1981, p. 8) also quotes the AAEC data.
[g] Above uranium deposit.

A difficult issue is estimating the actual radon released by *In Situ* Leach (ISL) mines, as currently in use at Beverley. The releases could be lower from ISL than conventional mining due to the lack of tailings and ore stockpiles, however, it is also likely that during operation the releases would be above normal baseline for the equivalent region being mined. An empirical model for estimating radon releases from ISL facilities was developed by Brown and Smith (1981), based on limited field sampling at an operational ISL mine. It was asserted that almost all of the radon released could be accounted for from the processing mill (99.95%) with a minor component from liquid waste storage ponds (0.05%). The well heads and waste scale buildup (e.g. calcite for their alkaline ISL project) were considered to be effectively 'zero'. The normalised radon release was estimated at 54 GBq/t U_3O_8, considerably lower than the 1088 GBq/t U_3O_8 estimate for underground uranium mining. Conversely, it was also estimated by Brown (1981) that an ISL mine has a normalised release rate of 143 GBq/t U_3O_8 (the discrepancy is unexplained).

4.3. Radon from ore, waste rock and low-grade ore stockpiles

As noted earlier, there is an increasing stockpile of ore, Waste Rock and Low-Grade Ore (WR–LGO) being produced in Australia. The available data for radon exhalation and releases are compiled in Table 9.

Table 7
Pre-mining and/or background radon exhalation and release surveys – South Australia and Western Australia

Location	Period or date of survey	Area (ha)	Exhalation (Bq/m^2/s)	Release (GBq/d)	References
Honeymoon[d]	April–June, 1980	–	0.033	–	Whittlestone (1980)
	1998		0.038		SCRA (2000)
Beverley[d]	1980	–	0.044	–	AMDEL (1982)
Paralana Hot Springs[a]	1980	–	10.6	0.54	AMDEL (1982)
Olympic Dam[d]	June 1991–May 1992	–	0.025	–	WMC (1992)
			0.005 → 0.035		
Yeelirrie[d]	November 1976	–	3.7	2159	WMC (1978b)
	1981	675	0.5 → 8	–	Leach et al. (1983)
Yeelirrie – regional background	Early 1980s (various)	–	0.05 → 3.5	–	O'Brien et al. (1986)
	November 1976	–	~0.74	–	WMC (1978b)
Lake Way					
Inner mine area[b,d]	4–17 September 1979	310	0.30	80	Casteleyn et al. (1981)
Outer mine area[c,d]		390	0.126	42	
Regional background		–	0.044	–	
Australian background	–	–	0.022 ± 0.005	–	Schery et al. (1989)

[a] Approximately 15 km west of Beverley.
[b] Distance of 0–2 km.
[c] Distance of 2–3 km from centre of proposed operations.
[d] Above uranium deposit.

As can be expected, there is a notably wide variation in the radon exhalation and releases from waste rock, low-grade and ore stockpiles. Some data may not be reliable, as the values seem either too high or low (e.g. 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 apparently no survey following rehabilitation works (1982–1986). At Yeelirrie, barometric

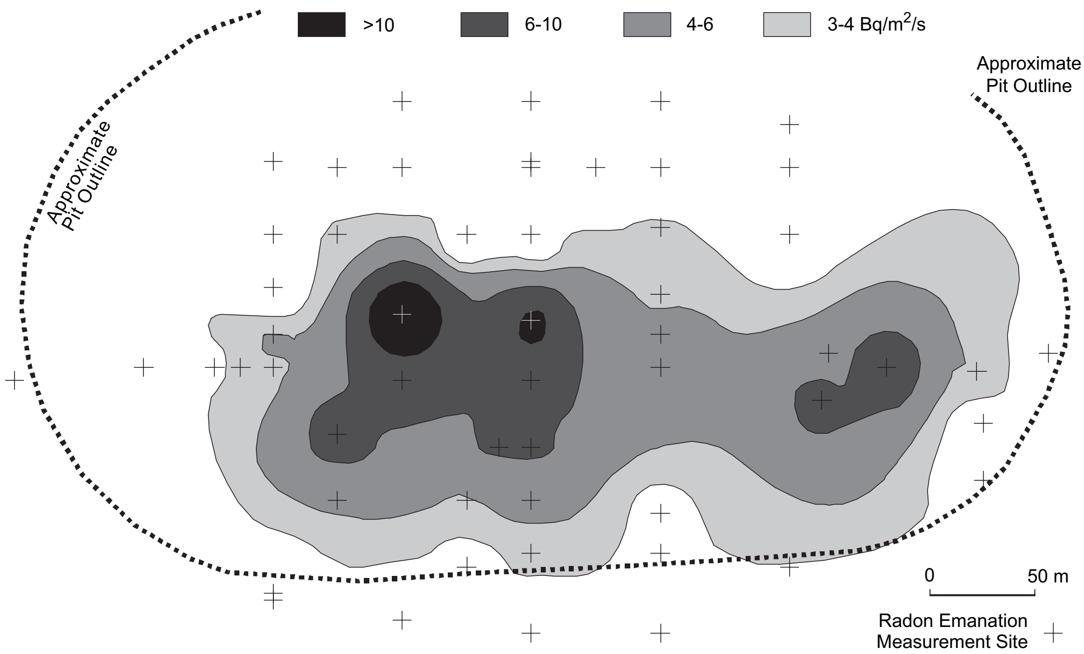

Fig. 4. Pre-mining radon exhalation measured at the Koongarra 1 uranium deposit, 1978 (mBq/m^2/s) (redrawn and adapted from Davy et al., 1978).

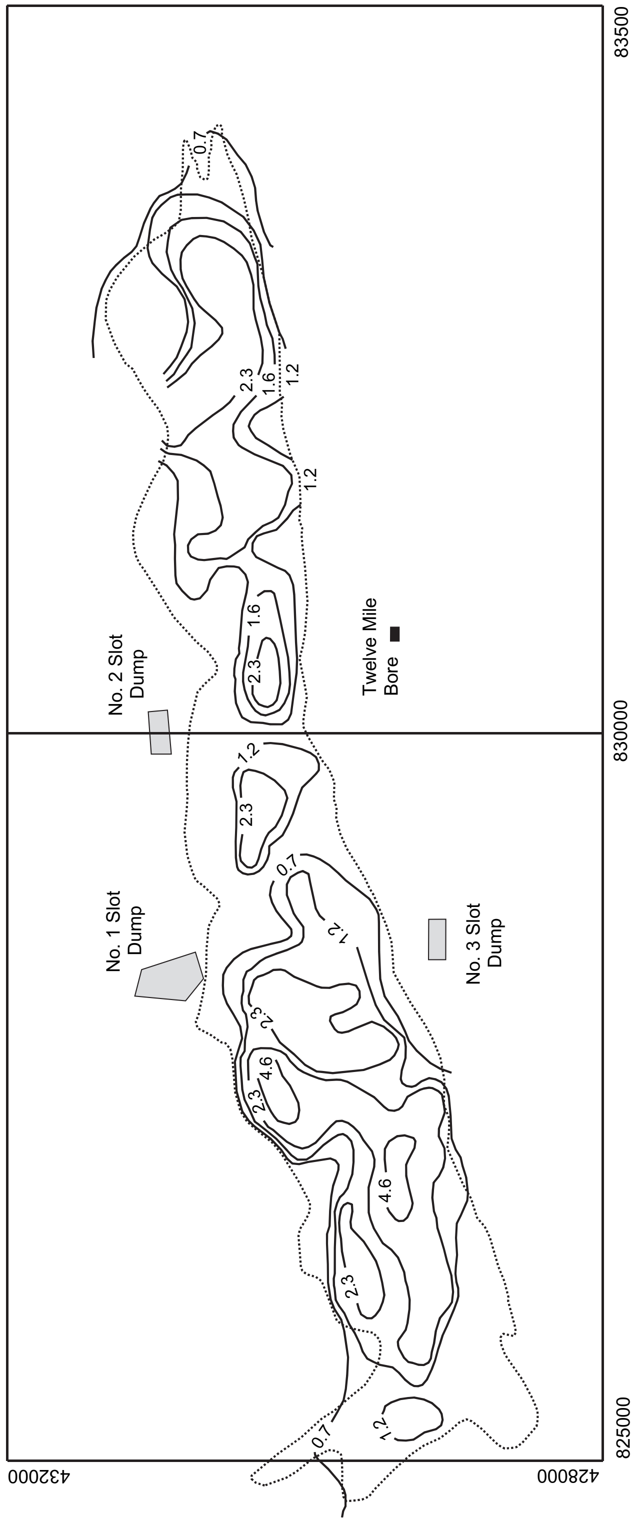

Fig. 5. Pre-mining radon exhalation measured at the Yeelirrie uranium deposit, June 1981 ($Bq/m^2/s$) (redrawn from Leach et al., 1983).

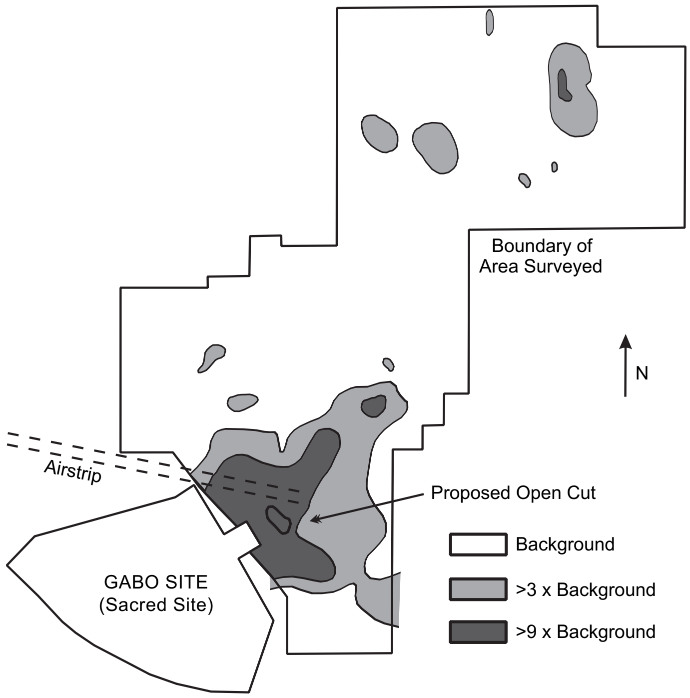

Fig. 6. Pre-mining radon activity in soil at Nabarlek (redrawn from QML, 1979).

pressure effects on radon exhalation have also been noted on early studies of the trial mine stockpiles (Brownscombe and Davy, 1978). The comprehensive study of the tropical Alligator Rivers Region by Lawrence (2006) shows clear seasonal behaviour in radon exhalation from waste rock dumps, related to the monsoonal wet season and resultant soil moisture (similarly, seasonal effects for radon activity in air have been noted earlier by Morley, 1981).

The effectiveness of rehabilitation works, such as engineered soil covers, could be expected to reduce radon exhalation somewhat though the sparse data are not convincing. For example, the study by Lawrence (2006) included radon exhalation measurements on an unnamed waste rock dump ($<$0.02% U_3O_8) and included a rehabilitated section. The radon exhalation was similar on both parts of the waste rock dump (see Table 9). Additionally, the study showed that radon exhalation cannot be expected to follow ore grade as the lower grade stockpile (the two stockpile, grade 0.02−0.08% U_3O_8) had a higher flux than the ore stockpile (the seven stockpile, grade $>$0.5% U_3O_8).

The radon released from normalised WR−LGO produced per GWe year could be based on previous mining data (i.e. 280 kt at ~0.02% U_3O_8 and 26 m high). Further discussion of waste rock and low-grade ore stockpiles is included in Sections 4.7 and 5.

4.4. Radon from 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 releases from mills have been made, almost entirely for EIS purposes for recent uranium projects. There still appears to be a lack of field measurements of radon releases from processing mills to verify EIS predictions. The available data are compiled in Table 10.

4.5. Radon from uranium mill tailings

One of the most significant (and controversial) sources of radon from uranium mining and milling, both during operation and after rehabilitation, is that from mill tailings. The predictions for radon exhalation and releases have varied significantly, depending on the chosen tailings management regime, although estimates for the same regime can also differ.

Table 8
Radon exhalation and releases from abandoned, operating, rehabilitated and proposed open cut and underground mines

Site	Source and conditions	Period of survey	Grade (%U_3O_8)	Area (ha)	Exhalation ($Bq/m^2/s$)	Release (GBq/d)	References
Ranger	Pit #1 – wall (three samples)	Oct. 2003	–	–	0.30 ± 0.05	–	Lawrence (2006)
	Pit #1 – bench (33 samples)				0.50 ± 0.05		
	Pit #3 – rocks (two samples)				1.0 ± 1.0		
	Pit #3 – pad (25 samples)				2.5 ± 0.6		
	Pit #3 – rubble (nine samples)				1.7 ± 0.7		
Jabiluka	Calculated estimate (underground mine)	~1996 (for EIS)	–	–	–	121	Howes (1997)
	Decline and mining cross-cuts	July–Aug. 1999	1.15	–	~17.3	–	Sonter (2000)
Coronation Hill	Old mining tunnel (adit)	Late 1980s	–	–	0.036 ± 0.057	–	DM (1988)
	Abandoned open cut mine				0.67 ± 0.46		
Yeelirrie	Open pits (operating) (proposed)	1978 EIS est.	–	–	~4.7	2463	WMC (1978b)
	Open pits (post-mining) (proposed)	1978 EIS est.	–	605.6	~1.2	602	WMC (1978b)
	Open pits (operating) (proposed)	1979 EIS est.	–	–	–	1918	WMC (1979)
Koongarra	Open pit mine (proposed)	1978 EIS est.	–	–	–	23–57	Noranda (1978)
Olympic Dam	Underground mine (operating)	1980–81	–		0.3 → 1 (avg) → 3	–	Kinhill (1982)
	Underground mine (proposed)	1982 EIS est.	–		–	700	Kinhill (1982)
	Underground mine (operating)	Jun 1992–May 1993	~0.083		–	120	Davey (1994)
	Underground mine (operating)	~1996	~0.08		–	121	Howes (1997)
Ben Lomond	Open pit mine (proposed)	1979 EIS est.	–	–	–	22.9	Minatome (1979)
	Underground mine (proposed)					38.4	
Ben Lomond	Pit – exposed ore (proposed)	1983 EIS est.	–	1	10	8.6	Minatome (1983)
	Pit – barren rock (proposed)		–	10	0.3	2.6	
	Underground mine (proposed)		–	–	–	3.2	

The available data for tailings-derived radon are compiled in Tables 11 and 12, including the sites where some rehabilitation works have been undertaken to date. The radon exhalation contours at the former Moline and Rockhole tailings are shown in Fig. 7. In 1986, half of the Rockhole tailings were excavated and transported to Moline, which were also re-excavated with all tailings emplaced within a new gold tailings dam (Mudd, 2000). There is no known radon exhalation survey at Rockhole or Moline since this time. Further to this, there are no known radon exhalation surveys for the Radium Hill tailings (McLeary, 2004a) nor publicly available for the Mary Kathleen tailings (they were undertaken but remain confidential).

The efficiency of water covers in reducing radon exhalation 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. (1998a) state that the radon released from Ranger's tailings to be 'zero', while other estimates for water covers have ranged between 7.4 (Fox et al., 1977) and 288 GBq/d (Davy, 1983), depending on the depth of water cover assumed. In the early years of operation, Davy (1983) estimated that exhalation 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 exhalation of 0.5 $Bq/m^2/s$. The significant difference between these estimates is due to the different regimes used for assessment and the assumptions adopted for the estimate, with some clearly being too optimistic (such as the 'zero') while others appear more reasonable. To date, however, there is no public data on the field-measured radon exhalation from water over the tailings facilities at Ranger (which currently cover about 150 ha).

Studies in Brazil have shown that approximately one third of the radon in mine water retention ponds is released to the atmosphere (Paschoa and Nóbrega, 1981). Based on laboratory column studies, Rogers and Nielson (1981) argued that the water covers on mill tailings facilities were a major radon source, and presented a model to estimate such releases. Using this model, as implemented by Diehl (2006a) and using Ranger's 1996 tailings configuration (1996 Edition, ERA, 1984–2005), a total radon exhalation of 3.01 $Bq/m^2/s$ can be calculated for a release of 296 GBq/d from the above ground tailings facility (allowing for the tailings area to be 60% under water >1 m, 10% saturated and 30% unsaturated) (additional data for the calculation sourced from Hart, 1986; Kvasnicka, 1986).

Table 9
Radon exhalation and releases from abandoned, operating, rehabilitated and proposed ore stockpiles and waste rock stockpiles

Site	Source and conditions	Period of survey	Grade (% U_3O_8)	Area (ha)	Exhalation (Bq/m^2/s)	Release (GBq/d)	References
Rum Jungle	White's waste rock dump (12 points)	Dry season 1981	0.01	26.37	1.1	25	Mason et al. (1982)
	RJCS waste rock dump (36 points)	Dry season 1981	0.054	15	2.7	35	Mason et al. (1982)
	Proposed rehabilitation	–	–	–	0.14	–	Allen and Verhoeven (1986)
Nabarlek	Ore stockpile (prior to cover)	~Oct. 1979	1.86	2.9	130	326	Leach et al. (1982)
	Ore stockpile (after cover)	~ Nov. 1979			38	95	Leach et al. (1982)
	Waste rock dump (20 points)	Dry season 1981	0.013	–	0.26	–	Mason et al. (1982)
Ranger	Waste rock dump (WRD) (unspecified)	~1989	–	–	–	18.0	Kvasnicka (1990)
	Waste rock dump (unspecified)	Jan.–May 1995	–	–	0.47	–	Kvasnicka and Auty (1996)
	Waste rock dump (unspecified)	Sept. 1996	–	–	0.519	–	Todd (1998)
	Tailings dam wall (low-grade ore)	Dry season 1981	0.013	–	0.21	–	Mason et al. (1982)
	Laterite stockpile – pad (20 samples)	August 2002	–	–	5.2 ± 0.6	–	Lawrence (2006)
	Laterite stockpile – push (seven samples)	August 2002	–	–	81 ± 15	–	Lawrence (2006)
	Laterite stockpile – rim (13 samples)	August 2002	–	–	38 ± 5	–	Lawrence (2006)
	Ore stockpile 2 – pad (15 samples)	Sept. 2002	0.02–0.08	–	10 ± 2	–	Lawrence (2006)
	Ore stockpile 2 – rim (10 samples)	Sept. 2002	0.02–0.08	–	7.3 ± 2.2	–	Lawrence (2006)
	Ore stockpile 7 – pad (nine samples)	July 2002	>0.5	–	3.1 ± 0.7	–	Lawrence (2006)
	Ore stockpile 7 – rim (eight samples)	July 2002	>0.5	–	0.95 ± 0.35	–	Lawrence (2006)
	Ore stockpile 7 – push (five samples)	July 2002	>0.5	–	1.7 ± 0.7	–	Lawrence (2006)
	WRD – pad (20 samples)	July 2002	<0.02	–	0.53 ± 0.1	–	Lawrence (2006)
	WRD – rehabilitated (21 samples)	July 2002	<0.02	–	0.94 ± 0.1	–	Lawrence (2006)
	WRD – overburden (four samples)	July 2002	<0.02	–	0.97 ± 0.17	–	Lawrence (2006)
Coronation Hill	Nearby adjacent areas	Mid 1980s	–	–	0.18 ± 0.28	–	DM (1988)
	Approximate background		–	–	0.062 ± 0.007	–	
Koongarra	Ore stockpile (proposed)	1978 EIS est.	–	–	70–184	–	Noranda (1978)
	Waste rock stockpile (proposed)		–	–	9–26	–	

(*continued on next page*)

Table 9 (*continued*)

Site	Source and conditions	Period of survey	Grade (% U_3O_8)	Area (ha)	Exhalation ($Bq/m^2/s$)	Release (GBq/d)	References
Yeelirrie	Stockpiles (various) (proposed)	1978 EIS est.	0.44	417.8	~1.6	566	WMC (1978b)
	Stockpiles (post-mining) (proposed)	1978 EIS est.		417.8	~0.9	339	WMC (1978b)
	Waste rock (trial mine stockpile)	Nov. 1976		Small	0.0015	–	WMC (1979)
	Stockpiles (various) (proposed)	1979 EIS est.		~400	2.82	975	WMC (1979)
Olympic 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)
	Waste rock (proposed)		0.0033	13.6	–	3.6	
	Ore stockpile – mill (proposed)		–	–	–	1.2	
Ben Lomond	Waste rock (proposed)	1983 EIS est.	–	10	0.5	4.4	Minatome (1983)
	Low-grade ore (proposed)		–	5	4	17.2	
	Ore stockpile – mill (proposed)		–	1	10	8.6	

Table 10
Estimated or measured radon releases from uranium processing mills

Site	Current status	Date of survey/estimate	Release (GBq/d)	Capacity (t U_3O_8/year)	References
Ranger	Operating commercially	1974 and 1975 EIS estimates	44	3000	RUM (1974, 1975)
		1977 Ranger Inquiry estimate	20 → 148	3000	Fox et al. (1977)
		1989 and 1992 Research estimates	147	3000	Kvasnicka (1990, 1992)
		1993 Research estimates	150	3000	Akber et al. (1993)
Beverley	Operating commercially	1998 EIS estimate	~101	~1000	HR (1998)
Honeymoon	Commercial mill proposed	2000 EIS estimate	484	~1000	SCRA (2000)
Olympic Dam	Operating commercially	1982 EIS estimate	16.4[a]	3000	Kinhill (1982)
		June 1992 → May 1993	57[b]	1351[c]	Davey (1994)
Yeelirrie pilot mill	Care and maintenance	1978 EIS estimate	0.19	~12	WMC (1978a)
Yeelirrie	Undeveloped	1978 EIS estimate	311	2500	WMC (1978b)
Koongarra	Undeveloped	1978 EIS estimate	46[a]	1375	Noranda (1978)

[a] Includes evaporation ponds.
[b] Assuming all radon is released during grinding and leaching.
[c] Approximate actual production during period of measurements.

Of interest at Olympic Dam is the effect of shrinkage cracks on radon exhalation, with a field study given by Storm et al. (1997) and Storm (1998). Based on this data, cracks can significantly increase the radon exhalation, and though the full extent awaits further field or laboratory studies, it could be as high as an order of magnitude. The proposed radon exhalation for rehabilitated tailings storage facilities at Olympic Dam, according to the 1982 EIS (Kinhill, 1982), was 1 Bq/m^2/s. This compares to the regional background radon exhalation of about 0.025 Bq/m^2/s (WMC, 1992). The 1997 Expansion EIS (Kinhill, 1997) discussed the need to reduce radon exhalation at the time of rehabilitation, however, no rate or quantitative objective was presented.

It can be seen in Tables 11 and 12 that both predicted and measured radon exhalation 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 (especially moisture content).

Another important issue to note is the change in radon exhalation at Nabarlek following rehabilitation. Prior to mining, radon exhalation was of the order of 4–44 Bq/m^2/s (Table 6), whereas they presently average 1 Bq/m^2/s following rehabilitation (Table 11). This is clearly the product of improved environmental planning and design at modern uranium mines. At Nabarlek, the high grade ore body outcropped at the surface but during mining the ore was buried in the bottom sections of the mined out pit and only contaminated soils and waste rock were emplaced in the upper sections of the pit, which was capped using waste rock and some soils (see Klessa, 2001). If there was no signature from the tailings (or other radium-containing materials), the radon exhalation should be within regional background. As such, the rehabilitated radon exhalation of 1 Bq/m^2/s shows a signature from radium-bearing materials near the surface. This is most likely to be related to the waste rock and radium-rich evaporation pond sediments emplaced in the upper section of the pit. A recent issue identified at Nabarlek, however, is a small region (0.44 ha) showing a strong radiation exposure within a land unit known as 'Erosion Unit 7' (Bollhöffer et al., 2006; Hancock et al., 2006). This region shows a high radon exhalation of 6.5 Bq/m^2/s and is thought to be due to erosion of a thinner soil cover in this area and exposure of the underlying contaminated soils scraped from the evaporation ponds during rehabilitation works, although the strong disequilibrium between ^{238}U and ^{226}Ra could suggest mill tailings. As noted by Bollhöffer et al. (2006), it is important to understand radon exhalation in terms of the radium activity as well as physical properties such as porosity, grain size and rock coverage.

There are continuing management issues at most tailings sites, e.g. Rum Jungle (Pidsley, 2002), Nabarlek (Bollhöffer et al., 2003; Iles, 2005), Mary Kathleen (Lottermoser et al., 2003), Radium Hill (McLeary, 2004a), Port Pirie (McLeary, 2004b) and Rockhole (Cochrane, 2000). There is nothing publicly available to ascertain the current status of neither the Moline tailings nor the Yeelirrie pilot mill tailings just north of Kalgoorlie. In order to improve the prospects for future tailings management, a more coherent picture and quantitative framework are clearly required based on well defined and reported field-measured data (and not merely assumed or asserted values, such as 'zero').

Table 11
Radon exhalation and releases from abandoned, operating, rehabilitated and proposed uranium tailings piles – Northern Territory and Queensland

Site	Source and conditions	Period of survey	Area (ha)	Exhalation ($Bq/m^2/s$)	Release (GBq/d)	References
Rum Jungle	Unrehabilitated tailings	1977–78[a]	~35	2.1	64	Davy et al. (1978), Ritchie (1985)
	Proposed rehabilitation target	–	–	0.14	–	Allen and Verhoeven (1986)
Nabarlek	Unrehabilitated dry tailings (lab)	1980s	–	32.2	139	Kvasnicka (1986)
	Final in-pit tailings (calculated)	1988 and 1996	–	3.63/4.71	–	Storm and Patterson (1999)
	UNSCEAR (1993) advised data	–	5	2.1	9.1	UNSCEAR (1993)
	Predicted rehabilitated tailings	–	–	$\sim 10^{-22}$	–	Storm and Patterson (1999)
	Rehabilitated tailings (actual)	Aug.–Sept. 1999	4	1.03 ± 0.80	3.6	Martin et al. (2002)
	Rehabilitated tailings (actual)	1999–2002	4	0.97	3.4	Bollhöffer et al. (2006)
Nabarlek	Radioactive anomalous area ('Erosion Unit 7')[b]	Oct. 2002	0.44	6.51 ± 6.83	2.5	Bollhöffer et al. (2006), Hancock et al. (2006)
Rockhole	Unrehabilitated tailings	June 25–27, 1982	~2	~6 (average) $<5 \rightarrow 21.1$	10.4	Bastias (1987)
Moline	Unrehabilitated tailings	June 19–23, 1982	~18	~2 (average) $<1 \rightarrow 17.9$	31	Bastias (1987)
Ranger	Unrehabilitated dry tailings (lab)	1980s	–	10.4	–	Kvasnicka (1986)
Koongarra	Proposed operational tailings	1978 EIS est.	–	–	260	Noranda (1978)
Ben Lomond	Proposed operational tailings	1979 EIS est.[c]	6.8	24.5	144.1	Minatome (1979)
		1983 EIS est.	24	0.3	6.2	Minatome (1983)

[a] Based on unpublished data quoted in the references (no date given). Number of sampling points was 24 with an average ^{226}Ra activity of 26.5 Bq/g.
[b] The source of the radioactivity in 'Erosion Unit 7' is considered to be tailings and contaminated soils scraped from the former evaporation ponds (Bollhöffer et al., 2006, pp. 321–322).
[c] Estimated ^{226}Ra activity of 17.1 Bq/g.

4.6. Radon from radium-contaminated areas

The radon exhalation and releases from areas of radium contamination remain poorly quantified. In general, the main areas which have received significant radium due to uranium projects are downstream of Rum Jungle and water management areas at Nabarlek and Ranger. The Magela Land Application Area (MLAA) at Ranger, which receives mine site runoff waters from Retention Pond 2 (RP2) elevated in magnesium, sulfate, uranium and radium, has had approximately 8.6 GBq of radium applied over about 51 ha between 1985 and 2004 (land application presently continues) (compiled and estimated from ERA, 1984–2005). Early research into the soils of the MLAA suggests that the radium is adsorbed within the topmost 5–10 cm of soil (Akber and Harris, 1991; Willett et al., 1993). This suggests an approximate increase in soil radium activity of about 100–200 mBq/g (assuming 1.6 t/m^3 for topsoil), a range consistent with soil monitoring of the MLAA (pp. 80–84, 2002 Edition, ERA, 1984–2005). A recent field study of the MLAA showed a radon exhalation of 0.112 $Bq/m^2/s$ (Akber et al., 2004), with further details in Lawrence (2006). Given the MLAA area of about 75 ha, this gives a radon release of up to 7.3 GBq/d.

4.7. Total project radon releases

The total radon releases released by uranium projects across Australia are 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 total radon release for the Olympic Dam project, based on computer modelling of measured radon decay products, has been estimated as 518 GBq/d by Crouch et al. (2005). This value is somewhat lower than those in previous tables, though it should also be noted therein that actual measurements are often different to predicted values (including both higher or lower values).

Table 12
Radon exhalation and releases from abandoned, operating, rehabilitated and proposed uranium tailings piles – South Australia and Western Australia

Site	Source and conditions	Period of survey	Area (ha)	Exhalation (Bq/m²/s)	Release (GBq/d)	References
Port Pirie	Unrehabilitated tailings	Survey 1 year	17.1[a] 4.5[b]	1.9 1.5 → 5.6 (avg) → 7.4	27.8 19.2	AAEC (1980)
Port Pirie	Covered tailings	Survey 1 year	17.1	0.12	1.8	Crouch et al. (1988), Hill (1986), Spehr (1984)
Olympic Dam	Proposed tailings (operating)	1982 EIS est.	400	0.6	207	Kinhill (1982)
	Covered Tailings	1982 EIS est.	400	1	346	Kinhill (1982)
	Operating Tailings	Jun 1997–Mar. 1998	380	1.24 → 3.5 (avg) → 8.2	1150	Storm (1998)
	Trial Covered Tailings	Mar. 1998	–	0.88	–	Storm (1998)
Lake Way	Proposed tailings (post-mining)	1981 EIS est.	–	0.75	–	BLA (1981)
Yeelirrie	Proposed tailings (operating)[c]	1978 EIS est.	330.3	~2.0	586	WMC (1978b)
	Proposed tailings (post-mining)	1978 EIS est.	330	~11.4	3261	WMC (1978b)
	Proposed tailings (operating)	1979 EIS est.	330	38.5	10,980	WMC (1979)

[a] Total area.
[b] Cells 2 and 3 only (majority of tailings).
[c] Includes radon sourced from pit dewatering operations (0.3 ha) pumped to the tailings dam for evaporation.

A realistic site for total release estimates is Ranger, since estimates for most components of radon releases are available. A preliminary compilation for total radon releases at Ranger is given in Table 13. It is noteworthy that the various estimates over time by different authors are quite variable, and perhaps even counter-intuitive to what could be expected. For example, a comparison of the pre-mine estimates with operational pit radon releases would

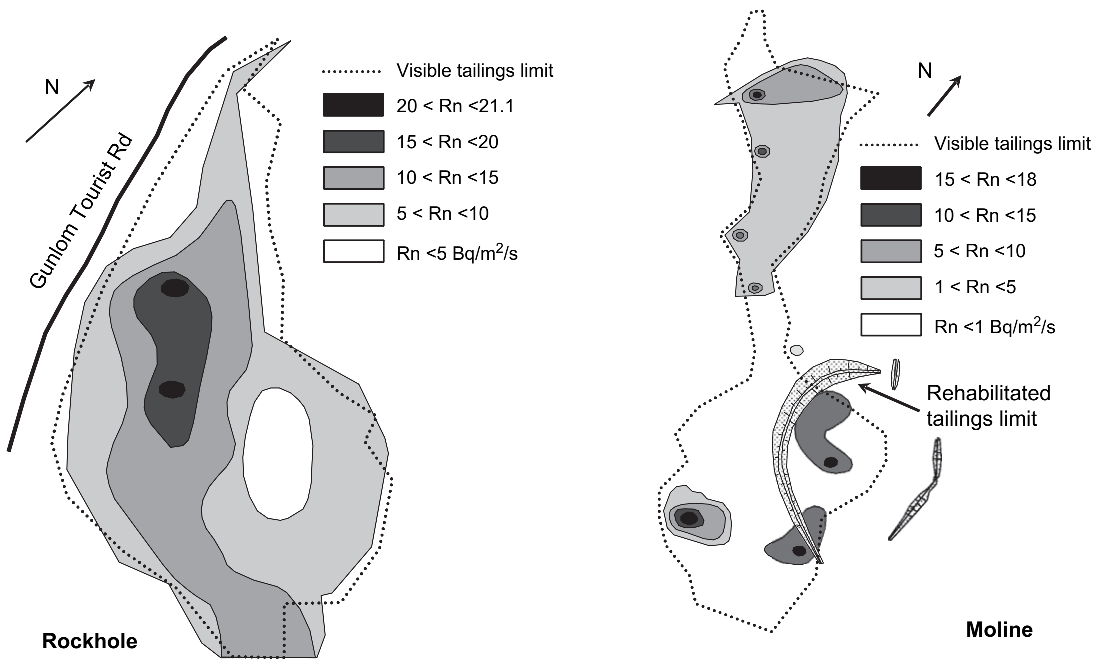

Fig. 7. Radon exhalation contours for uranium mill tailings before rehabilitation at Rockhole and Moline, June 1982 (no scale available) (redrawn from Bastias, 1987).

Table 13
Radon release estimates over time for the Ranger uranium project (GBq/d) (adapted from Mudd, 2002)

Year	Tailings management	Mill	Ore SP	WR	Pits	Tailings	Total	Reference
Pre-mine	–	0	0	0	372	5[a]	377	Auty and du Preez (1994)
1975	>2 m water cover	44	19[b]	–	32	<0.37	96	RUM (1975)
1977	–	20–148	~96[b]	–	20–281	14–144	150–669	Fox et al. (1977)
1981	Bare tailings (<12% moisture)	–	–	–	–	4105	–	Haylen (1981)
1981	Covered tailings (1 m clay, 2 m soil)	–	–	–	–	48	–	Haylen (1981)
1980s	Sub-aqueous deposition	–	–	–	–	197	–	Davy (1983), Author[c]
1989	Sub-aqueous and aerial deposition	147	318	18	34	148	665	Kvasnicka (1990)
1992	–	147	318	8	44	96	613	Kvasnicka (1992)
1993	Sub-aerial deposition	150	325	15	26	94	610	Akber et al. (1993)
1990s	Sub-aqueous and aerial deposition	–	–	–	–	77	–	Davy (1983)
1990s	Sub-aqueous and aerial deposition	–	–	–	–	296	–	Author[c]
2000s	Sub-aqueous and aerial deposition	150[c]	80[c,1]	163[c,2]	54[c,3]	299[c,4]	~750[c,5]	Author[c]

[a] Assuming a pre-mining exhalation of 0.05 $Bq/m^2/s$.
[b] Includes waste rock. WR, waste rock; SP, stockpiles.
[c] Values calculated/adopted from previous tables, as well as including new data from Lawrence (2006); [1]5 $Bq/m^2/s$ over 18.5 ha; [2]1 $Bq/m^2/s$ over 188.4 ha; [3]1 $Bq/m^2/s$ over 62.0 ha; [4]above ground dam and Pit #1; [5]includes small allowance for land application areas (as noted in Section 4.6).

suggest that open cut mining is actually leading to a lower radon release whereas logic would expect an elevated release due to the significantly increased surface area open to the atmosphere. The estimate of 4105 GBq/d from tailings by Haylen (1981) is an extreme estimate in comparison to others in Table 13 but is kept for completeness.

A compilation of the total of radon sources and uranium production levels is given in Table 14, to allow an estimate of the radon release relative to uranium production (i.e. GBq/t U_3O_8). The estimates, after allowing for data gaps, show that the radon release per tonne of uranium is quite variable and commonly between 30 and 100 GBq/t U_3O_8. For comparison to earlier ISL data (54–143 GBq/t U_3O_8), the Beverley acid leach mine releases approximately 37 GBq/t U_3O_8. There is little apparent difference between ISL, open cut and underground mining for Australian-produced uranium.

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 and low-grade ore, as well as other components which can sometimes provide significant radon releases, such as contaminated areas 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 is monitored in the surrounding environment, public radiological doses are estimated and provided these meet the relevant statutory requirements (i.e. <1 mSv/year), no further work has been considered necessary. This approach is inadequate, however, when setting rehabilitation standards and estimating long-term global doses as the releases are needed relative to the sources and operations at a specific uranium project. That is, we need to have a reliable estimate of the total radon released from the various source terms. Additionally,

Table 14
Predicted radon releases per unit Australian uranium production (GBq/t U_3O_8)

Project	Production	Radon release (GBq/d)							Unit release (GBq/t U_3O_8)	
	(t U_3O_8/year)	Mine	WR	Ore SP	Mill	Tailings	Minimum	Maximum	Minimum	Maximum
Beverley	1000				101		101	101	36.9	36.9
Ranger	5000	20–281	8–18	19–325	0–150	<0.4–299[a]	47.4	1073	3.5	78.3
Olympic Dam	4500	120–700			16–57	207–1150	343	1907	27.8	154.7
Yeelirrie	2500	600–2500	340–1000		311	586–11,000	1837	14,811	268.2	2162.4
Koongarra	1375	23–57			46	260	329	363	87.3	96.4
Ben Lomond	500	10–38	1–17			6–144	17	199	12.4	145.3
Nabarlek	1360		95			5–139	100	234	26.8	62.8

[a] Excluding the estimate by Haylen (1981) for bare, dry tailings as Ranger's tailings have never been operated in this manner.

it should be recognised that the changes in radon releases from uranium projects are cumulative across the industry (including reductions). Radiological monitoring and assessment should be also designed and undertaken in such a way as to include the ability to compare against pre-mining (or natural) conditions and how rehabilitation plans can be designed to achieve, at the very least, this level of performance. In this way, the cumulative changes across the industry can be argued to meet the ALARA principle and minimise doses.

5. Discussion

There are two major difficulties with estimating total radon releases from Australian uranium projects: (i) the lack of comprehensive data over time (including comprehensive pre-mining studies) 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 noted by Bollhöffer et al. (2003), in discussing the different radon exhalation values at the rehabilitated Nabarlek site, that discrepancies in measurement techniques and sample locations can affect overall results. Further significant issues are the geology and mining conditions for each deposit and the fact that almost all studies lack consistency on measuring or reporting moisture data. Given the critical importance of moisture and climatic differences, this remains a vexed issue. It is likely that these factors could explain, at least partly, some of the data variability within the tables.

Overall, this makes the direct comparison and use of the data somewhat problematic. Therefore, the detailed data compiled within this paper should be taken as indicative only. It should be emphasized that an assessment or calculation of radon releases from proposed and operating uranium projects should include all source term components (e.g. mine, mill, waste rock, stockpiles, tailings and mine site water ponds). The use of accurate field-measured data should be given the highest priority for studies on operating sites. For proposed sites, advantage can be taken of pilot milling and metallurgical research on ores to establish tailings' parameters, exploration data from drill cores, and so on. The practice of simply assuming data and other properties (as appears to be commonly undertaken in Australia at least) should be discouraged. The UNSCEAR analyses (UNSCEAR, 1993, 2000) both used assumed or approximated data for Australia – despite the available data from Australia (ignoring the somewhat disperse and often obscure location of some of the radon data).

It can be noted in the tables that for some older sites, both rehabilitated and abandoned, there is evidence of ongoing erosion problems leading to locally elevated radon exhalation (e.g. Nabarlek). Although measurements may be taken at a point in time, it is important to continually monitor and re-assess the radon sources of all sites, especially where population is nearby (e.g. Port Pirie) or some form of further land use is expected (e.g. Nabarlek).

In comparison to the UNSCEAR data, it would appear that Australia's equivalent tailings data are similar in dry density at 1.6 t/m^3 and also area at 0.95 ha/GWe year. To produce the 250 t U_3O_8 for 1 GWe year requires about 212 kt of 0.146% U_3O_8 ore, with radium 15.2 Bq/g and a tailings thickness of about 14 m. In addition, some 288 kt of waste rock and low-grade ore is produced at an approximate average of 0.02% U_3O_8, with radium 2.1 Bq/g and covering about 0.55 ha to a height of about 26 m. The radon releases can be predicted for these wastes using an online version of the US Nuclear Regulatory Commission's 'RAECOM' radon model (Rogers et al., 1984), as implemented by Diehl (2006b). The results are shown in Table 15. The UNSCEAR data, 3 Bq/m^2/s from 1 ha of tailings only, give a radon release of 2.6 GBq/d – compared to a possible range of radon releases for Australian-produced uranium of 2.9–12.6 GBq/d (tailings plus waste rock and low-grade ore). The total radon release depends on the combination of moisture content and emanation coefficient adopted, however, in any case the radon releases from Australian-produced uranium are likely to be higher than that assumed by UNSCEAR data. Rehabilitation works could reduce the long-term radon release but the field evidence is not convincing (e.g. erosion problems at Nabarlek leading to locally higher radon exhalation).

Given the widely varying conditions and compiled data, however, a standardised rate per GWe year is clearly not realistic; instead, site-specific and comprehensive field studies should be used. As noted previously, however, the UNSCEAR-style approach above ignores the additional sources from uranium projects, such as waste rock and contaminated areas, which can also be significant sources as shown in Tables 9 and 14. The long-term radon releases from waste rock and/or contaminated areas would clearly depend on the extent and effectiveness of rehabilitation works, with the sites for which actual post-rehabilitation radon exhalation data exist being restricted to Port Pirie and Nabarlek. In order to keep within the ALARA principle, it is therefore important to ensure that changes in radon releases are minimised – including waste rock, tailings and other potential sources.

Table 15
Predicted normalised radon exhalation and releases from Australian uranium for a standard reactor year (1 GWe year)

Waste	Moisture condition	Moisture (%dry weight)	Emanation coefficient	Exhalation (Bq/m^2/s)	Release (GBq/d)
Tailings	Dry	0.1	0.1	7.82	6.4
Tailings	Moist	8	0.25	14.17	11.6
Tailings	Saturated	31.3[a]	0.3	2.80	2.3
Waste rock and low-grade ore	Dry	0.1	0.1	1.23	0.58
Waste rock and low-grade ore	Moist	8	0.25	1.94	0.2
Waste rock and low-grade ore	Saturated	26.8[b]	0.3	0.15	0.07

[a] Saturated moisture based on calculated porosity of 0.50, based on the estimated average tailings particle density ('specific gravity') of about 3.2 (see tailings in Section 3.2).
[b] Saturated moisture based on calculated porosity of 0.43, based on the assumed waste rock particle density ('specific gravity') of about 2.8.

6. Conclusions

This paper has presented a detailed compilation and analysis of radon exhalation and releases from Australian uranium mining and milling projects. The primary purpose was to estimate normalised tailings and waste rock data and radon exhalation and release rates for a standard reactor year of uranium production to assess the efficacy of the UNSCEAR approach to long-term radon release from uranium mining (and consequent global population radiological doses). Overall, the UNSCEAR data for solid waste parameters are reasonable though it ignore potential major sources such as waste rock and low-grade ore. The extensive Australian data compiled for radon exhalation and releases for the various components of uranium mining and milling demonstrate wide variation and data quality, and show that waste rock and low-grade ores can be significant sources of radon. Importantly, the evidence on the effectiveness of rehabilitation works in reducing radon exhalation and releases is not convincing, especially when comparing cumulative changes from pre-mining conditions. Further work is required to ascertain whether this is due to design conflicts between revegetation or radon exhalation reduction requirements for engineered covers. When adopting more realistic data for tailings and waste rock, the UNSCEAR approach appears to underestimate the radon released from a standard reactor year of uranium production, though this needs to be moderated by the uncertain long-term effectiveness of engineered rehabilitation works. This paper has also shown that there is potential for uranium mining and milling to increase long-term radon releases into the adjacent environment relative to baseline or pre-mining conditions. In summary, these issues remain to be recognised in the broader debate about life-cycle analyses of uranium mining and nuclear power.

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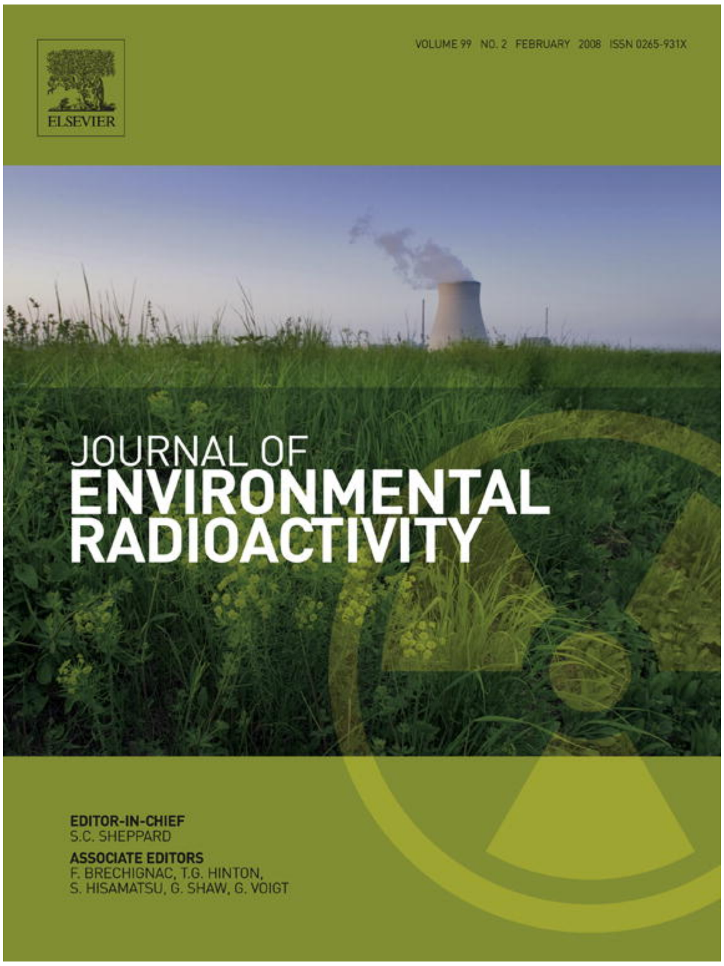
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