The Uranium Institute

Twenty-Third Annual Symposium
10–11 September 1998: London

Long Term Population Dose due to Radon from Uranium Mill Tailings

Douglas B Chambers, Leo M Lowe & Ronald H Stager

The European Commission has undertaken a study on the external costs (environmental and societal) of the various energy production systems, including nuclear power. The results of the study are likely to be one of the factors considered in determining how the European Union will develop its energy supply system. As a result, the study is of great interest to the nuclear industry, both in Europe and elsewhere. The Uranium Institute, the international trade association of the nuclear industry with some 78 members around the world, was asked by its membership to monitor the Commission's study, particularly with respect to nuclear power.

It came to the attention of the Institute that the radiation-related components of external costs for nuclear power are being based on the findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), with the costs being dominated by the estimated long term (10 000 year) collective population doses due to radon (considered to mean Rn-222 hereinafter) released from abandoned (but stabilised) uranium mill tailings. Unfortunately, the data used[1] are no longer appropriate for current and likely future conditions in the uranium mining industry, with the result that the estimated external costs of future nuclear power (potential environmental and societal costs) are overestimated.

Because of the importance of this issue to the nuclear industry in Europe and the worldwide uranium mining industry, the Institute retained SENES Consultants Limited to undertake a study using data that would be more current and appropriate for estimating population doses from radon, and therefore assist UNSCEAR in updating its estimates. The results of the study[2] are presented in this paper.

It is important to understand that the objective of this study was to examine long term population doses due to radon released from uranium mill tailings as it relates to the present and future generation of electrical energy. Since long term (10 000 year) population doses were being evaluated, radon release rates appropriate to tailings after decommissioning were considered. The releases during mining and prior to decommissioning are of relatively very short duration (generally less than 50 years) and were not considered in this study.

The collective population dose is proportional to the assumed duration of release. UNSCEAR[1] chose this value to be 10 000 years "for the sake of illustration". This value was also used in this study in order to compare the results to the UNSCEAR estimates.

Additionally, since radon from previously closed-out facilities will be released irrespective of the future of nuclear power, it was assumed that these sources need not be considered a factor in evaluating the externalities of current and future nuclear power production. For example, UNSCEAR (Reference 1, p136) shows that sites in the Elliot Lake, Ontario, region of Canada were the dominant sources of tailings-radon in Canada up to 1989. However, all these mines are closed and are no longer producing uranium, and the largest tailings areas are water-covered, thus eliminating the radon source term. The mines in western Canada (Saskatchewan) will be essentially the only source of Canadian uranium for nuclear power for the foreseeable future, and were the Canadian radon sources examined in this study.

A similar approach was taken in selecting the sites in other countries that were examined in this study. Essentially, the major uranium production facilities currently existing were examined in order to provide a snapshot of present day and likely future tailings management site conditions.

Tailings Sites Examined

In order to determine values of radon population doses that would be more representative of present day and likely future conditions than the values used by UNSCEAR, it was decided by the Institute that a survey of the major uranium production facilities be conducted. Information on radon release rate, tailings volumes, ore grades and production rates, likely decommissioning plans, and population densities was requested from various operators. It was requested that the information be based as much as possible on site-specific data.

The major mills in terms of uranium production in the 1995–97 period are shown in Table 1, based on data provided by the Institute. These were the facilities examined in this study. These facilities currently (1997) represent 67% of worldwide uranium production.

Although not specifically examined in this study, in-situ leach (ISL) facilities, which currently represent about 13% of worldwide uranium production, have no surface tailings and little radon emissions after closure.[3] Assuming the radon emissions from ISL facilities to be negligible, the results of this study could be considered to represent the impacts of long term radon emissions based on 80% of current uranium production.

The information used in this study can therefore be considered representative of worldwide conditions at the major uranium production facilities under current and foreseeable future tailings management practices.

Study Approach

Similar to the approach used by UNSCEAR, this study was limited to the use of modelled, generic air dispersion factors that were considered to be applicable to all sites. However, because of the potentially large (and unknown) uncertainties associated with this approach, and because of the availability to SENES of other air dispersion information for North America from previously completed projects, as well as census population data for Canada, more site-specific analyses were carried out for the Canadian sites.

Access to these data facilitated estimates of population doses using both actual and uniform population distributions, as well as comparison of air dispersion factors for a northern latitude site with results from a mid latitude site (Mexico) for which air dispersion parameters had also been compiled in the previous completed projects by SENES. By means of this comparative analysis, it was intended that the variability in the population doses and long range dispersion factors for two such quite different locations could be investigated and, in turn, would assist in quantifying the potential uncertainties associated

Table 1. Major uranium production facilities, 1995–97 (Source: The Uranium Institute).

	Mill facility	Owner/operator	Production (tU)		
			1995	1996	1997
Canada	Key Lake	Cameco/Uranerz	5 461	5 423	5 433
Canada	Rabbit Lake	Cameco/Uranerz	3 154	3 962	4 632
Australia	Ranger	Energy Resources of Australia	2 550	3 508	4 095
Namibia	Rössing	Rio Tinto (66%)	2 007	2 452	2 905
Niger	Akouta	COGEMA/Onarem	1 960	1 960	2 100
Canada	Cluff Lake	COGEMA	1 200	1 900	1 950
Australia	Olympic Dam*	WMC	1 108	1 466	1 425
Niger	Arlit	COGEMA/Onarem	1 000	1 200	1 350
		Total:	18 440	21 871	23 890
		% of total world production:	56%	62%	67%
		% of total world production less ISL:	65%	71%	77%
		In-situ leach (ISL) facilities (estimated)	4 391	4 400	4 601
		Total world production:	32 916	35 199	35 448

*Co-product with copper

Table 2. UNSCEAR assumptions used to derive population dose estimate for long term release of radon from uranium mill tailings (Source: UNSCEAR).

Uranium fuel requirements	210 tU (250 t U_3O_8) per GW-year of electrical energy
Normalised tailings surface area	1 hectare per GW-year
Radon release rate	3 Bq $m^{-2}s^{-1}$
Normalised emission rate	1 TBq per year per GW-year
Population density	3 km^{-2} < 100 km 25 km^{-2} 100–2000 km
Air dispersion factor at 1 km (release from semi-arid area at an effective height of 10 m)	3 x 10^{-6} Bq m^{-3} per Bq s^{-1}
Reduction in concentration with distance	$X^{-1.5}$ (X in km)
Dose conversion factor (equilibrium equivalent radon concentration)	9 nSv h^{-1} per Bq m^{-3} (EEC)
Radon progeny equilibrium factors	0.4 (indoors, occupancy 80%) 0.8 (outdoors, occupancy 20%)
Collective effective dose factor	0.015 person-Sv per TBq
Cumulative exposure period	10 000 years
Collective effective dose (range)	150 (1 to 1000) person-Sv per GW-year

with the use of the same dispersion estimates for all tailing sites.

UNSCEAR Estimates

UNSCEAR makes use of generic radon fluxes to estimate radon release rates and a generic air dispersion model to estimate the environmental radon concentrations as a function of distance from the site. UNSCEAR then converts the concentrations to population doses using assumed population densities for areas out to a distance of 2000 km and a radon dose conversion factor. Doses are accumulated over an assumed long term exposure period (10 000 years). The results are normalised to a unit amount of electrical energy produced. A summary of UNSCEAR assumptions, some of which were originally derived in Reference 4, is given in Table 2. These UNSCEAR assumptions are discussed below.

Uranium Fuel Requirements

UNSCEAR assumes that 210 tU (250 t U_3O_8) are required to produce 1 GW-year of electrical energy. Requirements are dependent on the reactor type, ranging from 180 tU for heavy water reactors to 330 tU for Magnox reactors (Reference 1, p105).

Normalised Tailings Surface Area

The basis for the 1 hectare per GW-year value is not given (originally used in Reference 5, p140). However, for perspective, the thickness of tailings, with a density of 1.6 t m^{-3} and a surface area of 1 hectare, resulting from the production of 210 tU from 1% uranium grade ore, would be about 1.4 m (assuming 92% recovery). This value is inversely proportional to the grade, with 0.3% ore requiring a thickness of about 4.8 m. In practice, however, tailings usually exceed these thicknesses, at least for the sites examined in this study, and therefore the area per unit of electrical energy produced is usually less than that assumed by UNSCEAR. (The radon release rate per unit surface area does increase proportionately with ore grade, but only minimally with increasing thickness beyond the first couple of metres of tailings.)

Radon Release Rate

The UNSCEAR unit radon release rate is based on reported emission rates ranging around 10 Bq $m^{-2}s^{-1}$, and the assumption that some reasonably impermeable cover would reduce the rate to 3 Bq $m^{-2}s^{-1}$ (Reference 1, p106; Reference 5, p140). The rate is assumed to be unchanged over at least 10 000 years because of the long radioactive half-life (80 000 years) of Th-230, the precursor of Ra-226.

As described in the next chapter, this rate substantially exceeds the rate expected for most of the tailings sites examined in this study, due to the planned covers and / or saturation of the tailings. The normalised emission rate of 1 (actually 0.946) TBq per year per GW-year is derived from the previous assumptions.

Population Density

The assumed population densities for the reference tailings site of 3 and 25 persons km^{-2} in the <100 km and 100 to 2000 km regions, respectively (Reference 1, p106), were originally derived from a 1975 study of tailings sites in the United States (Reference 4, p168).

While not unreasonable values for the rural, southwest United States, these densities are significantly greater than the densities derived for the sites examined in this study. The final estimate of the population dose is directly proportional to the assumed population density.

Air Dispersion Factors

The average air dispersion factor at 1 km and its reduction with distance for the model site were derived in part from a Gaussian plume model with a nominal source release height of 10 m and various assumptions about atmospheric conditions.[4,6] The factor at 1 km is 3 x 10^{-6} Bq m^{-3} per Bq s^{-1}. Beyond 1 km, and it was assumed that the concentrations decreased as $(\text{distance})^{-1.5}$.

If the assumed population densities and air dispersion factors are combined, and the radon progeny equilibrium factors (see below) are assumed to be constant with distance, then the total population dose is proportional to:

$$P_1 \, x \int_0^{100} r^{-1.5} \, 2 \, p \, r \, dr \; + \; P_2 \, x \int_{100}^{2,000} r^{-1.5} \, 2 \, p \, r \, dr$$

where P_1 and P_2 are the population densities (persons km^{-2}) in the <100 km and 100–2000 km regions respectively. Integrating this equation indicates that about 97% of the estimated population dose is for people living more than 100 km from the site for the population densities assumed by UNSCEAR. For a uniform population density across both regions, about 78% of the population dose would be for people living in the 100–2000 km region around the site.

It is not clear if UNSCEAR includes the decay of radon (3.82 day half-life) in its dispersion calculations. At a distance of 2000 km, and with an assumed 2.5 m s^{-1} average wind speed, the decay would reduce the radon concentrations by about a factor of five.

Dose Conversion Factor

The dose conversion factor of 9 nSv h^{-1} per Bq m^{-3} (equilibrium equivalent concentration, EEC) (Reference 1, p54) is based on now superseded dose factors that were derived using a dosimetric approach.

Subsequent to the publication of Reference 1, the International Commission on Radiological Protection (ICRP) published[7] a revised radon dose conversion factor for members of the public (derived by the ICRP using an epidemiological approach). The factor is 4 mSv per WLM (working level month) and is equivalent to 6.4 nSv h^{-1} per Bq m^{-3} (EEC), the value used in this study. (Based on the results from a recent meta-analysis of major epidemiological studies,[8] an even lower dose conversion factor[9] of less than 2 mSv per WLM may be appropriate.)

Radon Progeny Equilibrium Factors

The radon progeny equilibrium factors (Reference 1, p54) were based on several reported studies relative to typical background conditions, although there is some suggestion from some European and US studies that 0.6, rather than 0.8, might be a more representative outdoor factor. Using the 0.6 value would slightly reduce the time-weighted average equilibrium factor (considering indoor and outdoor occupancy) from 0.48 to 0.44.

These factors refer to typical background conditions. However, when relatively close to a source of radon, such as uranium tailings, the outdoor factor is much lower because there is insufficient time for radon progeny in-growth. For example, for an assumed 2.5 m s^{-1} average wind speed, the outdoor equilibrium factor at 1 km from a radon source would be about 0.1. (The indoor factor would be dependent on the air exchange rate of the building.)

Collective Dose Factors

The final estimate of the collective dose is directly proportional to the assumed cumulative exposure period of 10 000 years. UNSCEAR (Reference 1, p107) acknowledges that the estimated result of 150 person-Sv per GW-year (the same estimate obtained by Reference 5, p140) is highly dependent on a number of assumptions, including future tailings management practices, and they suggest a range from 1 to 1000 person-Sv per GW-year about their central estimate. The numerical basis for UNSCEAR's quoted range is not given.

Radon Source Terms and Population Densities

For this assessment, radon releases from the major, operating uranium production facilities were considered in the evaluation of the post-decommissioning source terms. The analysis did not consider radon from tailings areas no longer in use or which have previously been decommissioned. Similarly, as done by UNSCEAR, radon from mining and milling operations and from waste rock with residual trace radioactivity were not included in this analysis.

In order to develop a better understanding of the potential source terms, the operators of the major currently producing facilities were sent information requests. The following source term descriptions and population densities for the various sites were based on the responses, and on information supplied by the Uranium Institute and derived from publicly available literature.

The post-decommissioning radon source term estimates are summarised in Table 3. The population density estimates are summarised in Table 4. The bases for these estimates are in given in Reference 2.

Air Concentration Modelling

Modelling of long range transport requires sophisticated models, comprehensive meteorological data and extensive set-up effort. Existing data were available at SENES from previous studies to model long range transport for North American sites and two sites were selected. The first site was applicable to northern Saskatchewan meteorological conditions and the Canadian uranium mill tailings examined in this study, while the second (Mexico) was taken as representative of mid latitude meteorological conditions.

Analysis of the dispersion patterns for these two quite different regions provided information on how dispersion with distance varied. This analysis thus allowed some insight into the variability in the patterns of dispersion with distance that could be anticipated for mine sites at different locations. It was the intention of this analysis to illustrate the possible range of uncertainty associated with using the same air dispersion factors for all sites.

Northern Latitude Site

The dispersion modelling for northern Saskatchewan used information and methodology previously developed for a study of the long-range pollutant transport in North America.[17] The US Environmental Protection Agency (EPA) CALPUFF / CALMET modelling package was used to address long range flow patterns and the earth's curvature. Meteorological conditions were estimated for a 100 km by 100 km grid. Set-up effort is extensive for this type of modelling and,

Table 3. Estimated long term radon emissions from uranium tailings sites after decommissioning.

	Mill location/ name	Ore grade (%U)	Area (ha)	Flux ($Bq\ m^{-2}s^{-1}$)	Emission rate[b] ($MBq\ s^{-1}$)	Refs.	Comments
Australia	Ranger	0.30	63	0	0	10, 11	Long-term flux based on 12 m rock cover
	Olympic Dam	0.051	720	0.2	1.44	12, 13	Flux estimated for proposed rehabilitation plan
Canada	Key Lake[a]	13	24	0	0	2	Tailings water-saturated and covered
	Rabbit Lake	1.9	14	0	0	2	Tailings water-saturated and covered
	Cluff Lake	0.51	29	7	2.03	14	Based on current decommissioning strategy (thickened tailings and 1 m cover)
Namibia	Rössing	0.0298	750	1.2	9.00	15	Based on measurements on uncovered tailings; no reduction for future decommissioning assumed
Niger	Akouta	0.43	50	0.10	0.050	16	Flux estimated for future covered tailings (above a background flux of about 0.05 $Bq\ m^{-2}$). Ore grades based on mill averages to 1996
	Arlit	0.29	50	0.10	0.050	16	
UNSCEAR Model				3		1	Area normalised to 210 tU and 1 ha per GW-year

a. Key Lake tailings refers to tailings produced from both Key Lake ore and McArthur River ore to be milled at the Key Lake mill (see text)

b. The number of significant figures shown should not be considered indicative of the precision of the estimates.

Table 4. Population density around uranium tailings sites.

	Mill location/name	**Population density (km^{-2})**		
		<100 km	**100–2000 km**	**Refs.**
Australia	Ranger	0.054	1.8	10, 11
	Olympic Dam	0.21	1.5	2, 12
Canada	Key Lake	0.034	2.6	2
	Rabbit Lake	0.034	2.6	2
	Cluff Lake	0.034	2.6	2
Namibia	Rössing	2.1	5.2	15
Niger	Akouta	3.3	7.2	16
	Arlit	3.3	7.2	16
UNSCEAR Model		3	25	1

therefore, such detailed modelling could not be applied to other sites within the constraints of this project.

Concentrations from 100 to 2000 km were estimated using the CALPUFF / CALMET model and the existing data available to SENES. The US EPA ISC3 model was used to model concentrations from 1 km out to 100 km. The ISC3 model requires less set-up effort and provides reliable estimates over this range of distances. The modelled source, located at 58N and 103W and at a height of 1 m, had an emission rate of 1.0 Bq m^{-2}s^{-1} over a 250 000 m^2 area source for a total release rate of 0.25 MBq s^{-1}.

Theory predicts that concentration drops off quickly, by much more than a factor of r^{-1}, close to the source due to the combination of rapidly increasing area with distance and due to vertical mixing. At larger distances, concentrations tend to drop off by no less than r^{-1} since the mixing heights limit the vertical dispersion.

It is not clear if the UNSCEAR air dispersion modelling was done accounting for radioactive decay of radon (half-life of 3.82 days). As a result, the radon concentrations may be overestimated for this reason, especially at large distances from the source. For this study, a correction for removal of radon due to radioactive disintegration was developed based on the time required for the radon to reach the location. The average duration of transport from the source to the receptor was approximated by dividing the distance by a 2.5 m s^{-1} average wind speed. For example, the duration of transport to a receptor 2000 km from the source would be 9.3 days.

The corrected concentration (c) of radon at a receptor was approximated by:

$$c_{\text{corrected}} = c_{\text{modelled}} \text{ x } e^{-\lambda_r t}$$

where λ_r is the radioactive decay rate, 2.1 x 10^{-6} s^{-1}, of radon, and t is the elapsed time between release at the source and arrival at the receptor. The time was estimated by dividing the distance by a speed of 2.5 m s^{-1} (as estimated from the North American meteorology). The method estimates that radon concentrations at 2000 km distance from the source would be about 19% of modelled values assuming no radioactive decay (about a factor of five lower).

Concentrations were summarised for 16 directions from the source and the mean, maximum, and minimum concentrations are plotted on Figure 1 in comparison to those predicted by UNSCEAR dispersion factors. Concentrations drop off rapidly with distance with mean levels decreasing from about 300 mBq m^{-3} at 1 km from the source to 0.3 mBq m^{-3} at a distance of 100 km (a factor of 1000 lower). The mean concentration is lower than 0.001 mBq m^{-3} at a distance of 2000 km and continues to drop at increasing distances due to both ongoing dilution and the radioactive decay of radon. The ratios of the predictions using the UNSCEAR dispersion model to the predicted mean values in this study range from about two at a distance of 10 km to 17 at a distance of 2000 km.

The incremental radon levels at all distances are much lower than typical outdoor radon concentrations, which are in the order of 10 000 mBq m^{-3} (Reference 1, p54).

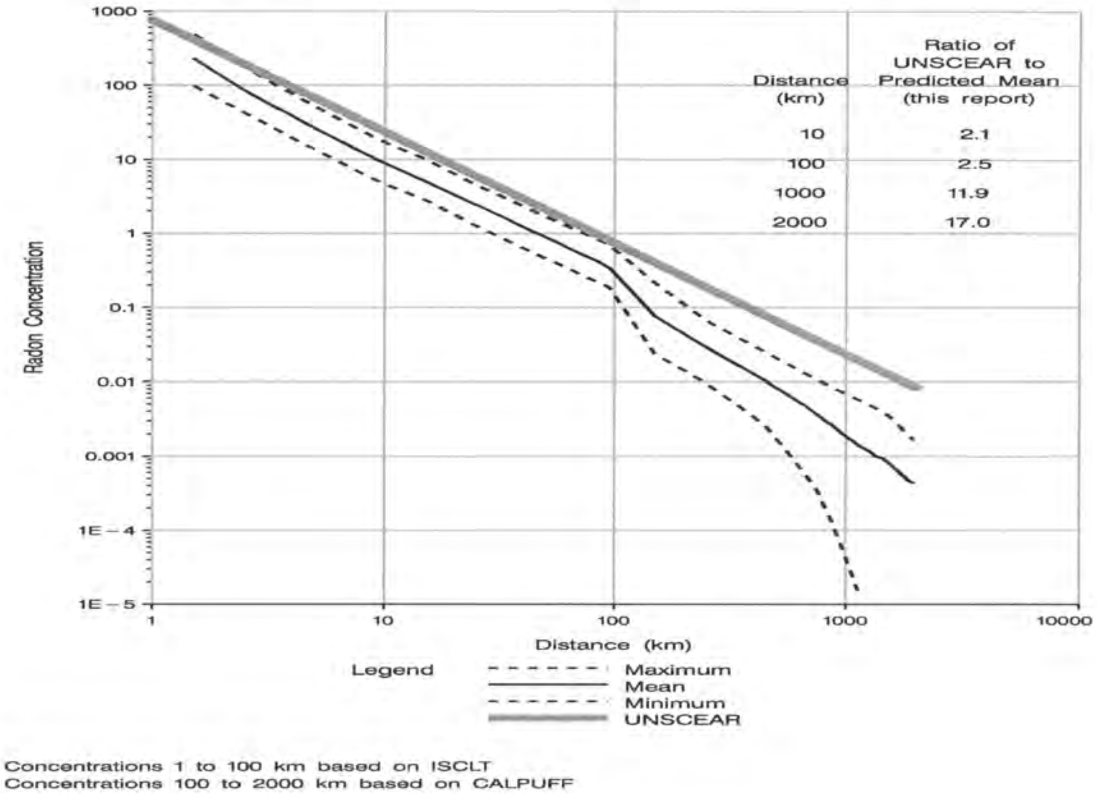


Figure 1. Predicted radon concentrations (mBq m^{-3}) against distance, for northern Saskatchewan site.

Mid Latitude Site
Radon concentrations were estimated for the 100 km by 100 km North American grid with the source located at 25.5N and 103.0W in Mexico. Although no uranium facility is present at this location, the site was selected to illustrate dispersion characteristics in the mid latitudes of the Northern Hemisphere.

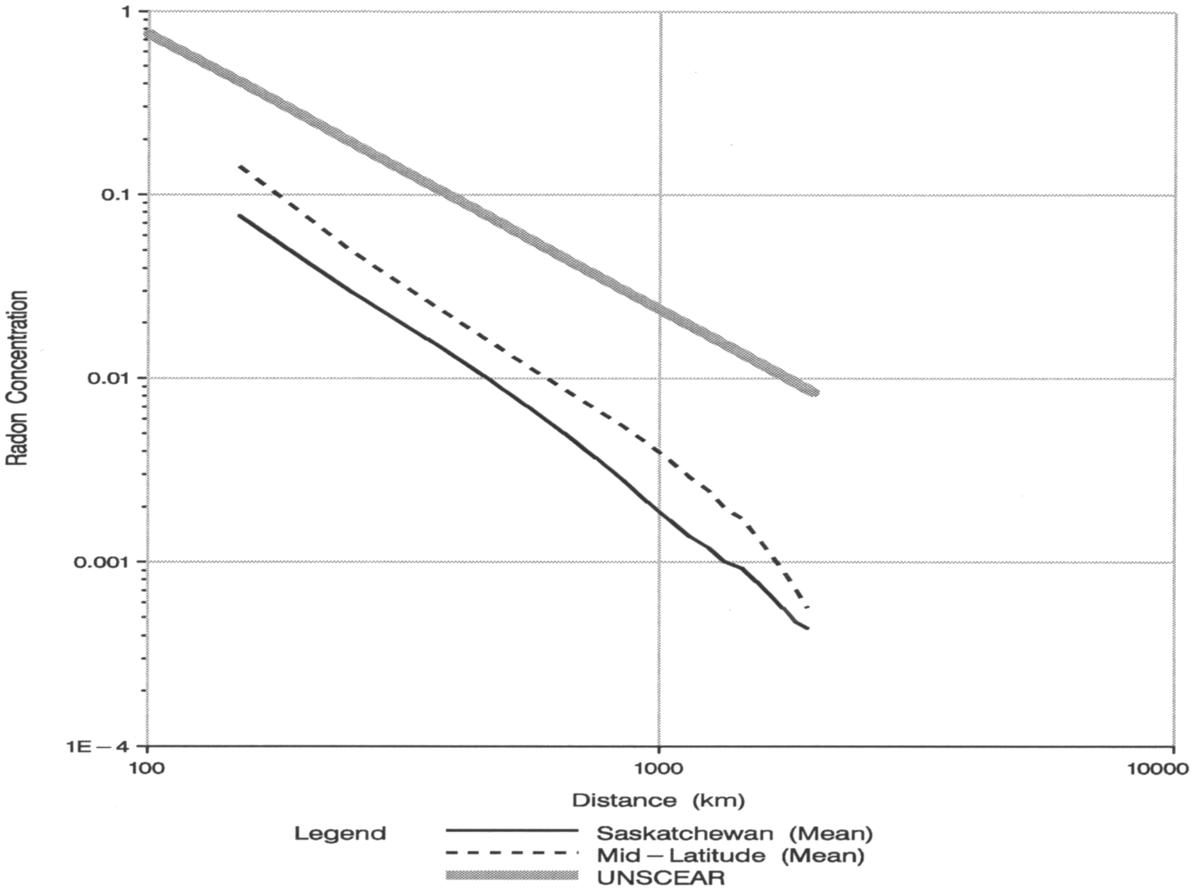
Figure 2 shows the pattern of concentrations with distance for both the northern Saskatchewan and mid latitude locations for distances of 100 to 2000 km from the source in comparison to concentrations predicted using UNSCEAR's dispersion model. Mean concentrations for the mid latitude location are higher (by about a factor of two) than those calculated for the northern Saskatchewan location. (Although not shown, the maximum and minimum concentrations (i.e. upwind or downwind) vary by about a factor of 10 for the mid latitude location.)

Reference Concentrations
Concentrations for the sites examined in this study were estimated based on the 1 to 100 km mean concentrations estimated using for northern latitude (Saskatchewan) meteorology, and the 100 to 2000 km mean concentrations using the mid latitude (Mexico) meteorology. Concentrations were prorated by the ratio of site-specific emission rates to the reference case emission rate, 0.25 MBq s^{-1}, used in the dispersion modelling described previously.

The dispersion factors, and hence concentrations, used by UNSCEAR and those derived in this study for the northern Saskatchewan region differ by factors of two to three in the <100 km region. However, the differences increase with distance, with the difference being up to a factor of about 17 (with UNSCEAR concentrations larger) at 2000 km. This may be due in part to the effect of radon decay that was accounted for in this study and which reduces concentrations by about a factor of five at 2000 km.

Population Dose Estimates

Population exposure estimates were based on multiplying the population size in an area by the average radon concentration in the area. This section describes the population exposure estimates for each mining area that were estimated by multiplying the average (area-weighted) site-specific concentration in the <100 km and 100 to 2000 km regions by the site-specific uniform population density in the regions.



Source emitting 0.25 MBq s^{-1}
Concentrations based on CALPUFF
Two different meteorological conditions

Figure 2. Predicted radon concentrations (mBq m^{-3}) against distance, based on two different meteorological conditions.

Since concentrations decrease rapidly with distance, the true distribution of population within the area can significantly impact the population exposure. In order to examine the potential impacts of using a uniform rather than a true population distribution, population exposure estimates by distance from the source were investigated in detail for the northern Saskatchewan site. Site specific population distributions were not available for the other sites. In this situation, population exposure estimates were found to be about a factor of three to four lower if the true population distribution with distance were used as compared to the assumption of uniform population density within the two regions, i.e. the <100 km and about three times lower for the 100 to 2000 km regions.

The long term (10 000 year) population dose estimates for the uranium tailings sites examined in this study are summarised in Table 5. The normalised estimates range from 0 to 5.9 person-Sv per GW-year, with an overall 1997 production weighted average of 0.96 person-Sv per GW-year. These estimates may be compared to the UNSCEAR central estimate of 150 person-Sv per GW-year. The way in which the estimates for each site were derived is described in Reference 2.

Background Doses

People living around the eight sites examined in this study will be exposed to background radon, irrespective of the operation of uranium production facilities. For the total of 2.11 x 10^8 people around the sites (counting only one in each country in order not to double count people), the total background dose is given by:

$$14.4 \text{ Bq m}^{-3} \times (2.11 \times 10^8) \times (6.4 \times 10^{-9} \text{ Sv h}^{-1})(\text{Bq m}^{-3})^{-1} \times 8.76 \times 10^3 \text{ h y}^{-1} \times 10^4 \text{ y} = 1.7 \times 10^9 \text{ person-Sv}$$

The assumed 14.4 Bq m^{-3} (EEC) average background radon concentration was derived from Reference 1 as follows. The previously noted outdoor concentration of 10 000 mBq m^{-3} (10 Bq m^{-3}) converts to 8 Bq m^{-3} (EEC) based on an outdoor radon progeny equilibrium factor of 0.8. The indoor concentration of 40 Bq m^{-3} converts to 16 Bq m^{-3} (EEC) based on an indoor equilibrium factor of 0.4 (Reference 1, p54). For 80% indoor occupancy and 20% outdoor occupancy, these concentrations give an overall average of 14.4 Bq m^{-3} (EEC).

This is probably a conservative (low) dose estimate because background concentrations in areas with uranium deposits are generally higher than typical background levels. The dose of 1.7 x 10^9 person-Sv per 10 000 years is a factor of 366 000 larger than the total population dose of 4650 person-Sv for all the sites examined in this study. These results are discussed in more detail in the next section.

Comparing UNSCEAR and SENES Estimates

The overall, normalised population dose estimate in the SENES study of 0.96 person-Sv per GW-year of electrical energy produced is about a factor of 150 lower than UNSCEAR's estimate[1] of 150 person-Sv per GW-year. The more recent and site-specific information obtained for the SENES study was not available to UNSCEAR, which had to rely on generic radon emission and population data for its estimates.

UNSCEAR[1] provided a range of 1 to 1000 person-Sv per GW-year about their central estimate of 150 person-Sv per GW-year. The central estimates for every site examined in this study were below the UNSCEAR central estimate, while the central estimates for six of the sites were below UNSCEAR's suggested bottom range estimate of 1 person-Sv per GW-year. Some of the more significant parameters that contribute to these differences in the estimates are discussed below.

Radon Emission Rates

Based on the information summarised in Table 3, the long term emission rate of radon from tailings used by UNSCEAR substantially exceeds the rates expected for the most of the tailings sites examined in this study. While the value of the long term emission rate at any site is certainly speculative (especially to 10 000 years), it is clear that UNSCEAR's central estimate did not account for the current and short term future tailings management practices that would essentially eliminate radon emissions at some sites i.e. saturated, water-covered tailings. The lower estimate of 1 person-Sv per GW-year given by UNSCEAR does indicate that it acknowledges the uncertainty in its estimate (and specifically that its estimate may be too large), although the numerical basis for its estimated range is not given by UNSCEAR.

Normalised Emanating Area of Tailings

The UNSCEAR estimate of 1 hectare per GW-year differs from (overestimates) the surface area of tailings based on more recent data, or, conversely, underestimates the thickness of tailings, and correspondingly the amount of potential electrical

Table 5. Emissions from uranium tailings sites.

	Mill location/name	Production rate (1997)[a] (tU y^{-1})	Normalised population dose[b] (person-Sv per GW-y)
Australia	Ranger	4 095	0
	Olympic Dam	1 425	0.12
Canada	Key Lake	5 433	0
	Rabbit Lake	4 632	0
	Cliff Lake	1 950	2.7
Namibia	Rössing	2 905	5.9
Niger	Akouta	2 100	0.078
	Arlit	1 350	0.10
		23 890	0.96

a. From Reference 2.
b. Assuming 210 tU per GW-year (see text).

energy, associated with the radon emissions. This increases the final estimate of person-Sv per GW-year, especially for the deeper (thicker) tailings areas. Deeply buried tailings essentially contribute zero radon to the environment but the ore associated with those tailings does result in the production of electrical power.

Population Density

The overall population densities assumed by UNSCEAR for its modelled tailings site typically overestimate the current population densities at the sites examined in this study. Data collected for this study shows that for the <100 km region, the ratios of the UNSCEAR estimate of 3 persons km^{-2} to the site-specific densities range from 0.9 to 88.2. The ratios for the 100–2000 km region range from 3.5 to 16.7, whereas the UNSCEAR estimate is 25 persons km^{-2}.

This study also examined the effects of using uniform, rather than actual, population distributions as a function of distance around a tailings site. For the Saskatchewan site, for which data were available to this study, the assumption of uniform (i.e. two region) distributions overestimates the cumulative population dose by about a factor of 2.5. While this difference is not necessarily applicable to other sites, the analysis indicates the magnitude of one of the sources of uncertainty associated with the final dose estimates.

Air Dispersion Factors

As in the SENES study, UNSCEAR makes use of generic air dispersion factors in assessing the dispersion of radon released from the decommissioned tailings. The air dispersion factors derived in this study compare within a factor of about three with the UNSCEAR factors at distances <100 km, but diverge from the UNSCEAR factors, by factors of four to 10 and more, in the 100–2000 km region.

The analyses carried out in this study suggest that only part of this difference in the distant region is due to site-specific parameters, since the direction-averaged dispersion factors for the northern latitude (Saskatchewan, Canada) and mid latitude sites (Mexico) differed by less than a factor of two. Not accounting for radon decay with distance also appears to have contributed to UNSCEAR's higher estimate (relative to this study) of the air dispersion factors. If radon decay were to be included in the UNSCEAR values, the air dispersion factors derived in this study would be within about a factor of three of the UNSCEAR values.

Uncertainties

Similar to the UNSCEAR long term population dose estimates, the estimates derived in this study are inherently uncertain. Some of the sources of this uncertainty are qualitatively discussed below.

How Representative are the Sites?

The eight sites examined in this study are currently (1997) responsible for 67% of the world's production of uranium. (As previously noted, the results of the study could be considered to represent the impacts of long term radon emissions based on 80% of current worldwide uranium production if allowance is made for in-situ leach facilities.) However, the conditions at other production facilities may be significantly different than at these major producers, in terms of population densities and especially in terms of overall radon emission rates per unit of potential electrical energy produced. The overall population dose for all existing facilities may therefore be different.

Nevertheless, given that tailings management practices are continually evolving and that the sites examined here may be considered representative of likely future practices, the estimate derived in this study is probably a fair representation of conditions in the foreseeable future.

Other Fuel Cycles

The population dose estimates from both this study and UNSCEAR were based on assumed uranium fuel requirements of 210 tU per GW-year. Other fuel cycles, including reprocessing, could significantly lower fuel requirements and would correspondingly result in lower population doses per GW-year due to radon emissions from uranium tailings.

Population Growth

The population dose estimates were based on current (generally within 10 years) population densities. There is the potential for long term population growth but the rate and numbers over the very long term (10 000 years) is unknown. On a worldwide basis, and considering that the earth's resources are finite, the long term population is unlikely to be more than a factor of five to ten larger than today's population. On the other hand, in the <100 km region, because many of the uranium producing facilities are in remote locations, the local populations may well decrease once those facilities are no longer operating.

All this is clearly speculative, but the uncertainties due to population growth affect both the estimates derived in this study and the UNSCEAR estimate. The estimated population doses from background radiation would also be affected by population growth.

Population Distribution

As discussed above, the assumption of uniform (two region) population densities resulted in nearly a threefold overestimation of population dose for the northern latitude site, based on the actual population distribution. A similar or greater magnitude of overestimation or underestimation could exist at any site. The location of the population relative to wind direction causes larger uncertainties, by factors of five to 15 when comparing maximum (downwind) and minimum (upwind) population doses (Table 5). These uncertainties are equally inherent in the UNSCEAR estimate of population dose.

Air Dispersion Factors

Air dispersion characteristics, especially near-field, can be very site-specific. However, except for sites that might have population centres located generally downwind of the site in the <100 km region, the largest population dose will occur to people living in the 100–2000 km region. The air dispersion factors estimated in this study for both a northern and mid latitude site were comparable (within a factor of two), but smaller than the UNSCEAR dispersion factors. If radon decay (up to a factor of about five at 2000 km) were included in the UNSCEAR dispersion factors, the latter would also be comparable (within a factor of about three) to the dispersion factors used in this study.

Overall Uncertainty

The major objective of this study was to estimate the normalised (to unit of power produced) long term population dose due to radon emitted from uranium tailings, using the same methodology as UNSCEAR but based on more site-specific information. A quantitative uncertainty analysis of the results was beyond the scope of work for the study. However, the following qualitative comments are offered.

The contribution to the overall uncertainty due to imprecision in the site-specific information (overall radon emission rate, population densities, and the potential amount of uranium associated with the tailings) is likely to be much smaller than from the uncertainty in other factors that affect the estimation of population dose. Considering the uncertainties in population distributions within each region (<100 km and 100–2000 km), meteorological dispersion, the air dispersion model and overall population growth, the overall uncertainty range for sites with specific information is subjectively estimated at about a factor of ten about the central estimate.

A reliable estimate of the population dose for sites not considered in this study (corresponding to about one-fifth of current world production) cannot be made at present because their site-specific conditions (radon emissions, population densities, etc.) were not available.

Other Issues

Perspective on the Estimated Doses

Notwithstanding the uncertainties associated with the analyses undertaken here, it is perhaps informative in terms of perspective to examine the magnitude of the estimated radon exposures and doses.

The total long term (10 000 year) population dose to radon emissions from the uranium tailings sites examined in this study is about 4650 person-Sv. Using the ICRP's nominal probability coefficient of 0.06 total cancers per person-Sv,[18] this population dose converts to about 280 cancers over 10 000 years, or less than three cancers over a typical lifetime. This may be compared to the more than 60 million background cancers expected in the lifetime of the approximately 210 million people living within 2000 km of the sites (assuming a 30% background cancer incidence rate). The 4650 person-Sv estimate is a factor of 366 000 below the background population dose of 1.7×10^9 person-Sv for the same sites.

The area-weighted concentrations in the <100 km region are factors of 200 or more lower than background concentrations. A large fraction (3720 person-Sv or 80%) of the population dose is incurred by people living beyond 100 km of the sites. The area-weighted average radon concentrations in the 100–2000 km region around the sites are estimated to range from near zero to about 0.2 mBq m^{-3}. These concentrations are factors of more than 50 000 lower than typical outdoor background concentrations.

Linear No-Threshold Model

The population doses estimated in this study and by UNSCEAR implicitly assume the validity of the linear, no-threshold (LNT) dose response model; that is, the risks of exposure to radiation are assumed to be directly proportional to the dose received, down to zero dose. There is much current discussion of the appropriateness of the LNT model for estimating impacts from doses that are extremely small fractions of natural background radiation. The presence of a dose threshold, even a practical threshold in which competing causes of death defer the risk from radiation beyond the expected lifespan for detrimental effects, or of a hormetic effect, would render any assumed impacts associated with the population doses estimated in this study or by UNSCEAR invalid.

Integration Period

To be comparable to the UNSCEAR estimate, the population doses estimated in this study were integrated over a 10 000 year exposure period. While UNSCEAR chose this period for illustrative purposes, the assumption that conditions for which the dose estimates were derived would be constant over this period is clearly speculative.

However, it is quite likely that total or at least partial cures for some of the potential cancers associated with radiation exposure would have become available in the 10 000 year time period. On this basis, notwithstanding the issues associated with the LNT model noted previously, or from future improvements in medical care of cancer, it is likely the any impacts associated with the population doses derived in this study or by UNSCEAR will be overestimates of the actual (if any) impacts.

Conclusions

The major conclusions from the present study are:

- Based on the site-specific data available to this study, UNSCEAR's generic estimate of radon emissions from uranium tailings sites is too large for the sites examined in this study.
- Relative to the assumption of uniform (two region) population densities, the use of site-specific population distributions can result in significantly different (larger or smaller) population dose estimates.
- The radon concentrations associated with the tailings emissions are extremely small on both a relative (compared to typical background levels) and absolute (in terms of dose and risk) level. In the authors' view, the individual risk of cancer associated with the predicted concentrations is below a level that can be considered completely insignificant and trivial, i.e. *de minimis*.
- The uncertainties in the estimates provided in this study were reduced relative to the uncertainty in the UNSCEAR estimate because of the availability of more site-specific data on radon emissions and population densities. Further refinement of the analyses would require the use of site-specific meteorological data and population distributions.
- UNSCEAR's central estimate of the long term (10 000 year) population dose due to radon emissions from uranium mill tailings is too large, by about a factor of about 150, based on site-specific data and current and proposed tailings management practices at the sites examined in this study.

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