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RISKS TO CAVERS AND CAVE WORKERS FROM EXPOSURES TO LOW-LEVEL IONIZING α RADIATION FROM ^{222}RN DECAY IN CAVES

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Abstract: Human health risks posed by exposure to elevated levels of ^{222}Rn in caves are not well documented. Various studies throughout the world have detailed the often very high ^{222}Rn gas concentrations in caves and exposures to cavers and commercial tour guides and other employees, but without a consequent assessment of the overall impact on human health. Although ^{222}Rn concentrations in caves are considered high relative to most above ground dwellings, the levels identified are also considered to be low for ionizing α radiation. Low-level ionizing radiation impacts on human health are deduced by application of the linear no-threshold theory (LNT) of radiation carcinogenesis. Comprehensive reviews of the published literature and an understanding of exposure time suggests that commercial cave workers (e.g., tour guides) and commercial ^{238}U-mine workers are both exposed for the same number of hours per month (~170 h), but cave workers are exposed to much lower ^{222}Rn concentrations than are mine workers. Cavers will generally be exposed for a smaller number of hours per month. Risk estimates suggest that cavers will likely be subject to insignificant risks, but that cave workers may be subject to low-level risks of developing lung cancers from elevated levels of ^{222}Rn gas concentrations in caves.

Introduction

This paper was developed to provide the National Speleological Society reader with an intensive investigation of the potential health effects posed by exposure to elevated levels of radon in caves. To the author's knowledge, no other publication on radon in caves has delved into the risks to cavers from exposure to radon in caves to the extent that this paper does.

Radon-222 is generally regarded as a naturally occurring inert radioactive gas with a half life of 3.824 days and is produced within the ^{238}U decay series (Fig. 1), the process of which is described in detail in Field (1994, p. 52–60) and where the phenomenon of radioactivity is described in detail in Ivanovich (1992, p. 1–33). In fact, ^{222}Rn is only partly inert. Radon-222 may also be regarded as a metalloid[1], an element that lies on the diagonal of the Periodic Table between the true metals and nonmetals (Fig. 2). Because ^{222}Rn is a metalloid, it exhibits some characteristics of both metals and nonmetals, such as forming a series of clathrate compounds[2] (inclusion compounds), and reacts readily with fluorine and fluorides (Stein, 1987; Cigna, 2005).

Radon-222 poses a substantial threat to human health when build-up occurs in confined spaces such as homes, mines, and caves (ICRP, 1994a, p. 1) and when exposure time is sufficiently long. The average annual per person radiation dose from exposure to ^{222}Rn from caves is estimated to be 1 nSv (0.1 μrem)[3], although cavers and cave workers are expected to receive much higher doses (ATSDR, 1997, p. 217). Show caves are a recognized hazard in terms of ^{222}Rn exposure to cave workers (tour guides, maintenance personnel, employees working in shops built over cave entrances, etc.) (IAEA, 2003, p. 5–6 and 46), but because of the sensitive nature of cave environments, high ^{222}Rn gas concentrations cannot easily be remediated (IAEA, 2003, p. 60). Forced air ventilation in caves is regarded as unthinkable because of the likely deleterious effects on the microclimates and biota (Yarborough and Meyers, 1978, p. 28 and 73). The U.S. Environmental Protection Agency (EPA) believes that the risks posed to human health by low levels of ^{222}Rn gas in single-family residences to be more significant than the risks to uranium miners exposed to very high levels of ^{222}Rn gas because the miners are only exposed for 170 h per month in the mine (1 Working Level Month) while homeowners spend more time in their dwellings and receive a greater overall exposure (Abelson, 1991). The principal threat is by the formation of lifespan shortening lung cancer, pulmonary emphysema, and pulmonary fibrosis through damage to the respiratory epithelium (Samet, 1997; Cross, 1987, p. 215–216).

The existence of elevated concentrations of ^{222}Rn in caves is well established in the literature (Table 1). Table 1 is a sampling of the literature that contains extensive ^{222}Rn concentration values, but does not list all of the basic literature on caves and ^{222}Rn (see for example, Cigna, 2005; Gunn, 2003, p. 617–618). However, the risks to

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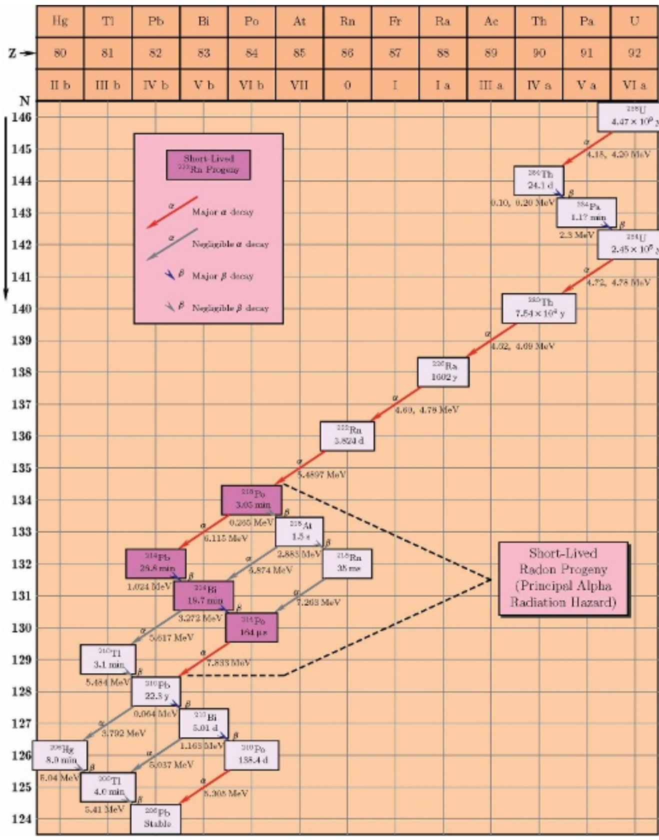

Figure 1. Uranium-238 decay series. The horizontal scale, Z, is the number of protons in the nucleus, and the vertical scale, N, is the number of neutrons in the nucleus. Also shown are the half-lives, type of decay (either by α- or β-particles), and the major radiation energies (in MeV) of ^{238}U and its progeny. Modified from Cothern (1987, p. 7) and NRC (1988, p. 26). Negligible percentage decays included even though they are not a human health concern. See Table 12 in the Appendix for the historic names of the ^{222}Rn progeny.

cavers and cave workers from exposure to the relatively high ^{222}Rn concentrations in caves are poorly understood and rarely reported in the literature (Kobal et al., 1986, 1987; Vaupotič et al., 1998, 2001).

The purpose of this paper is to explore the risks posed to the health of cavers and tour guides as a result of exposure to low-level ionizing radiation from ^{222}Rn gas and its progeny. Radon-219 and ^{220}Rn (commonly known as thoron) do not represent as serious a concern as does ^{222}Rn because (1) ^{219}Rn is relatively rare and has a very short half life ($T_{1/2}$ = 4 s) and (2) ^{220}Rn has a very short half life ($T_{1/2}$ = 56 s) (ATSDR, 1990, p. 11). Radon-219 has only rarely been found at elevated levels in caves (Yarborough and Meyers, 1978, p. 42).

Particular attention will be directed at the linear no-threshold theory (LNT) of radiation carcinogenesis because this is the accepted model for estimating risks posed by exposure to ^{222}Rn gas and its progeny (Dicus, 2001; Kellerer and Nekolla, 2000; NCRP, 2001; NAS, 2005; NRC, 1999, p. 69) even though there is some dispute as to its appropriateness (e.g., Bond et al., 1996; Cohen, 2000). There is, however, good reason to continue relying on the LNT even with all its attendant problems because it is a reasonable risk model (Oughton, 2006).

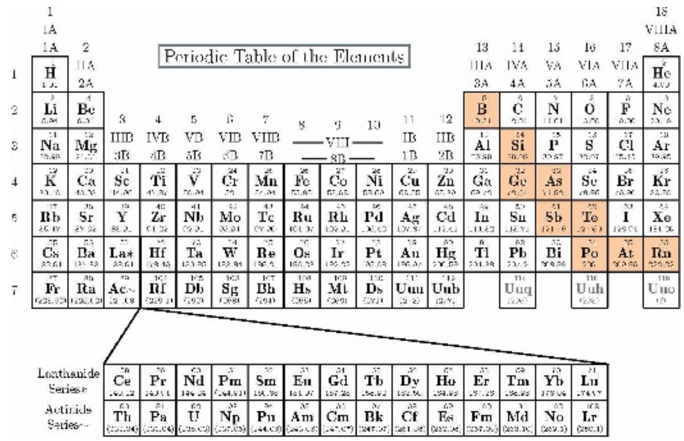

Figure 2. Arrangement of the metalloid elements (dark shading) in the Periodic Table (modified from Stein (1987).

THREATS POSED BY ^{222}Rn AND ITS PROGENY

Radon-222 is the heaviest of the noble gases and because it is a relatively nonreactive gas that exists everywhere in the environment, it tends to migrate to and concentrate in enclosed spaces (e.g., basements, caves, tunnels, etc.). However, ^{222}Rn is not a major health risk by itself.

High concentrations of ^{222}Rn progeny (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) are widely recognized as a source of lung cancer and possibly other cancers (Henshaw et al., 1990; Bridges et al., 1991) through the emission of α- and β-particles with dense ionization along their tracks although it is the α-particles that are most responsible for the resulting high-linear energy transfer (LET)[4] because of its large +2 charge and relatively large mass (~8,000 times that of an electron). Emission of β-particles (high-energy electrons) results in low-LET because of its ±1 charge and much smaller mass than α-particles. In either case, both low and high LET interactions can cause significant DNA damage (ATSDR, 1997, p. 30–31), but it is the densely ionizing radiation produced by α-particle decay that causes many double strand DNA breaks that are most difficult for cell repair and are most likely to give rise to cancer formation (Craven and Smit, 2006). According to Craven and Smit, sparsely ionizing radiation typically results in single strand DNA breaks which are much easier for cells to repair.

Cothern (1989) states that "between 4,000 and 30,000 fatal lung cancers occur each year due to exposure to radon in indoor air," but does not offer any supporting data or references for such a contention. The EPA had projected

Table 1. Summary of ^{222}Rn literature (modified from Hyland and Gunn (1994). Note that many of the references include ^{222}Rn measurements from several sources[a].

Country	Mean ^{222}Rn Concentration (Bq m^{-3})	Number of ^{222}Rn Measurements	Max. ^{222}Rn Concentration (Bq m^{-3})	Min. ^{222}Rn Concentration (Bq m^{-3})	Reference
Australia	610	274	4,045	9	Solomon et al. (1996)
China[b]	141	32	278	38	Wiegand et al. (1995)
Czech Republic	1,235	60	21,000	200	Burian and Stelcl (1990)
Great Britain	2,907	820	46,080	10	Hyland and Gunn (1994)
Great Britain	…	2,000	155,000	100	Hyland and Gunn (1994)
Great Britain	35,890	34	155,000	7,400	Gunn et al. (1991)
Great Britain	9,306	13	12,552	68	Gillmore et al. (2000)
Great Britain	365	42	3,187	26	Gillmore et al. (2002)
Great Britain	315	28	3,047	34	Gillmore et al. (2002)
Greece	25,179	6	88,060	185	Papastefanou et al. (1986)
Hungary	3,300	25	14,000	500	Somogyi et al. (1989)
Hungary	2,468	8	13,200	200	Lenart et al. (1990)
Ireland	4,127	26	7,940	200	Duffy et al. (1996)
Japan	11	5	20	< 1	Miki and Iauthora (1980)
Malaysia	596	39	1,978	100	Gillmore et al. (2005)
Poland	1,166	279	4,180	60	Przylibski (1999)
Russia	2,390	14	8,550	373	Gunn (1991)
Slovenia	1,412	101	7,220	15	Kobal et al. (1986)
Slovenia	965	66	5,920	60	Kobal et al. (1987)
Spain	108	301	488	5	Dueñas et al. (1998)
Spain	3,564	8,587	7,120	186	Lario et al. (2005)
South Africa	267	63	2,319	3	Gamble (1981)
Switzerland	25,000	6	40,000	2,000	Surbeck (1990)
United States	1,927	60	9,350	37	Yarborough (1976)
United States	2,589	11	9,460	370	Eheman et al. (1991)
United States	1,475	…	2,350	740	Ahlstrand (1980)
United States	…	860	1,850	333	Ahlstrand and Fry (1976)
United States	11,678	37	82,177	11	Bashor (undated)

[a] Data quality control likely varies for each study conducted for each country which should be regarded as problematic.
[b] Measurements taken in Chinese cave dwellings built in the Chinese Loess Plateau which is mainly composed of Mesozoic sandstones overlain by Tertiary red clays that are covered by Quaternary loess tens to over one hundred meters thick (Wiegand et al., 1995) where the number of inhabitants exceed three million (Yanada, 2003)

14,000 lung-cancer deaths per year from residential ^{222}Rn exposure with an uncertainty range of 7,000 to 30,000 (Page, 1993), but now estimates 21,000 lung-cancer deaths per year from residential ^{222}Rn exposure with an uncertainty range of 8,000 to 45,000 (U.S. EPA, 2006). In fact, the expected lung cancers and other adverse health effects may be more a result of smoking than of inhalation of ^{222}Rn gas (Pisa et al., 2001). In addition, the expected lung cancers in cavers and cave workers appear to be conspicuously missing from the published literature, perhaps because no one has yet linked lung cancers in cavers and cave workers to long-term exposure to high ^{222}Rn concentrations (Halliday, 2003).

Risks to cavers and cave workers by exposures to high levels of ^{222}Rn may not be as serious as is often presented. The potential overestimation of the risks posed by elevated levels of ^{222}Rn and the belief by many individuals that overestimation may actually be the case, have caused some consternation among some researchers (Cothern, 1989, 1990; Little, 1997). The possibility that ^{222}Rn and its progeny may be responsible for some cancers other than lung cancer also is not strongly supported in the literature (Tomasek et al., 1993). For example, Law et al. (2000) were unable to establish an association between household exposure to ^{222}Rn and the development of leukemia in adults in Great Britain. Lauier et al. (2001) obtained similar results.

A significant reason why ^{222}Rn and its progeny may not be as serious a threat to cavers and cave workers may be because although ^{222}Rn concentrations in caves are considered to be elevated, these levels are also considered to be relatively low in terms of ionizing radiation. For example, employees exposed to radiation in the work place in Great Britain (e.g., cave tour guides) are not allowed to receive annual effective radiation doses[5] above 50 mSv yr^{-1} (10 WLM yr^{-1}) with an action level of 15 mSv

Table 2. Inhalation exposure studies of ^{222}Rn (modified from ATSDR, 1990, pp. 13–15). Superscript numbers next to each entry correspond to data point numbers in Figure 3.

Species	Exposure Frequency/ Duration	Effect	NOAEL ($Bq\ m^{-3}$)	LOAEL (Effect) Less Serious ($Bq\ m^{-3}$)	LOAEL (Effect) Serious ($Bq\ m^{-3}$)	Reference
<u>Acute Exposure</u>						
Mouse[1]	1 d	Death			8.14×10^9 (30 d LD_{50})	Morken (1955)
Mouse[2]	1 d	Hemato			8.14×10^9 (anemia)	Morken (1955)
	5–40 h					
<u>Intermediate Exposure</u>						
Rat[3]	4–6 mo	Death	1.11×10^5			Chameaud et al. (1984)
	$2\ d\ wk^{-1}$					
	$1\ h\ d^{-1}$					
Rat[4]	Lifespan	Death			1.78×10^8 (dec lifespan)	Palmer et al. (1973)
	$2\ d\ wk^{-1}$					
	$90\ h\ wk^{-1}$					
Mouse[5]	Lifespan	Death			1.55×10^7 (dec lifespan)	Morken and Scott (1966)
	$150\ h\ wk^{-1}$					
Hamster[6]	Lifespan	Death			1.78×10^8 (dec lifespan)	Palmer et al. (1973)
Rat[7]	Lifespan	Resp			1.78×10^8 (metaplasia)	Palmer et al. (1973)
	$2\ d\ wk^{-1}$	Other		1.78×10^8 (dec bw)		
	$90\ h\ wk^{-1}$					
Mouse[8]	Lifespan	Resp			1.55×10^7 (metaplasia)	Morken and Scott (1966)
	$150\ h\ wk^{-1}$	Hemato		1.55×10^7 (dec lymph)		
		Other		1.55×10^7 (dec bw)		
Mouse[9]	Lifespan	Resp			1.78×10^8 (fibrosis)	Palmer et al. (1973)
	$2\ d\ wk^{-1}$	Other		1.78×10^8 (dec bw)		
	$90\ h\ wk^{-1}$					
Hamster[10]	Lifespan	Resp			1.78×10^8 (metaplasia)	Palmer et al. (1973)
	$2\ d\ wk^{-1}$	Other		1.78×10^8 (dec bw)		
	$90\ h\ wk^{-1}$					
Dog[11]	1–50 d	Resp			2.04×10^7 (fibrosis)	Morken (1973)
	$5\ d\ wk^{-1}$					
	$20\ h\ wk^{-1}$					
Rat[12]	2.5–8 wk	Cancer			1.11×10^7 (CEL-lung)	Chameaud et al. (1982)
	$4\ d\ wk^{-1}$					
	$3–6\ h\ d^{-1}$					
Rat[13]	25–115 d	Cancer			2.78×10^7 (CEL-lung)	Chameaud et al. (1974)
	$4–5\ h\ d^{-1}$					
Rat[14]	6–6 mo	Cancer			1.11×10^7 (CEL-lung)	Chameaud et al. (1984)
	$2\ d\ wk^{-1}$					
	$1\ h\ d^{-1}$					

Table 2. Continued.

Species	Exposure Frequency/ Duration	Effect	NOAEL (Bq m^{-3})	LOAEL (Effect) Less Serious (Bq m^{-3})	LOAEL (Effect) Serious (Bq m^{-3})	Reference
Chronic Exposure						
Hamster[15]	Lifespan 5 d wk^{-1} 6 h d^{-1}	Death	1.15×10^{7}			Cross et al. (1978)
Hamster[16]	>1 mo−18 yr (occup)	Resp			>3.70×10^{3} (tuberculosis)	Waxweiler et al. (1981)
Hamster[17]	Lifespan 5 d wk^{-1} 6 h d^{-1}	Resp			9.62×10^{6} (hyperplasia)	Cross et al. (1978)
		Hemato	1.15×10^{7}			
		Other		9.62×10^{6} (dec bw)		
Human[18]	0.5–23 yr (occup)	Cancer			1.26×10^{4} (CEL-lung)	Gottlieb and Husen (1982)
Human[19]	(occup)	Cancer			7.40×10^{3} (CEL-lung)	Morrison et al. (1981)
Human[20]	0–14 yr (occup)	Cancer			3.70×10^{3} (CEL-lung)	Solli et al. (1985)
Human[21]	>29 yr (occup)	Cancer			2.22×10^{3} (CEL-lung)	Edling and Axelson (1983)
Human[22]	>1–>20 yr (occup)	Cancer			1.85×10^{3} (CEL-lung)	Damber and Larsson (1985)
Human[23]	48 wk yr^{-1} 48 h wk^{-1} (occup)	Cancer			1.85×10^{3} (CEL-lung)	Howe et al. (1987)
Human[24]	>10 yr (occup)	Cancer			1.11×10^{3} (CEL-lung)	Snihs (1973)
Human[25]	>2–30 yr (res)	Cancer			5.55×10^{1} (CEL-lung)	Svensson et al. (1989)
Human[26]	(occup)	Cancer			8.88×10^{3} (CEL-lung)	Fox et al. (1981)
Human[27]	>1 mon–18 yr (occup)	Cancer			3.70×10^{3} (CEL-lung)	Waxweiler et al. (1981)
Human[28]	>1 mon–30 yr (occup)	Cancer			1.48×10^{4} (CEL-lung)	Roscoe et al. (1989)

CEL = Cancer Effect Level
hemato = hematological
resp = respiratory
occup = occupational
dec = decreased
bw = body weight
res = residential

(1.5 rem) (Hyland and Gunn, 1994). This total annual effective dose of 50 mSv yr^{-1} is also applicable in some instances in the United States (U.S. Navy, 2001, p. 4-1 and NRC, 2005, p. 5), although 20 mSv yr^{-1} (4 WLM yr^{-1}) is generally the accepted level (OSHA, 1988, 41 CFR §57.5038) while the NCRP (1993, pp. 34–35) has suggested more flexibility to control worker exposure. However, low-radiation doses are considered to range from near 0 to 100 mGy[6] (0 to 10 rad), medium doses from 100 mGy to 1 Gy (10 to 100 rad), and high doses from 1 Gy to 20–60 Gy (100 to 2,000–6,000 rad) (NRC, 2005, p. 374).

By this definition it would appear that an action level based on an effective dose of 15 mSv may be overly protective. The human equivalent dose H_T is estimated using Equation (1)

$$H_T = \sum_R W_R \, D_{T,R} \qquad (1)$$

and the effective dose E_D is estimated from

$$E_D = \sum_T W_{T_i} \sum_R W_R \, D_{T,R} \qquad (2)$$

Using $W_R = 20$ for α-particles (ICRP, 1980, p. 94) results in an absorbed dose $D_{T,R}$ of 0.75 mGy, which is at the lower spectrum of a low-radiation dose. Using $W_{T_L} = 0.12$ for the lung (0.24 for lungs) (ICRP, 1991, p. 68) results in 6.25 mGy which is still at the lower spectrum of a low-radiation dose.

^{222}RN PROGENY

Although it is true that ^{222}Rn represents a risk to cavers in terms of lung cancer, its relatively long half life (3.824 d) will more often result in the exhalation of ^{222}Rn prior to emanation of an α-particle that could penetrate the epithelium of the lung to cause a cancerous growth. So even though the energy associated with the emission of an α-particle from ^{222}Rn is relatively high (5.49 MeV) and it is possible that α-particle emission from inhaled ^{222}Rn gas may have an adverse affect on human health, it is not likely that α emission will actually occur during the time that the ^{222}Rn gas resides in the lung. This situation is considerably different for ^{222}Rn progeny.

The four ^{222}Rn progeny (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) are either metals (^{214}Pb and ^{214}Bi) or metalloids (^{218}Po and ^{214}Po) that are relatively short-lived and emit α-particles with relatively high energy and β-particles with relatively low energy (Fig. 1). It is these features, principally the α-particles, that represent the main risk posed by ^{222}Rn. Each of the four principal ^{222}Rn progeny are quite reactive, which causes them to plate-out[7] in the lung as well as enhancing their tendency to adsorb to smoke and dust particles. The risk of lung cancer occurrence is exacerbated by smoke and dust particles because these metals and metalloids readily react with and adsorb to the particles which are easily inhaled.

Threats from ^{218}Po

Polonium-218 has a half life of 3.05 min and is the immediate progeny resulting from the decay of ^{222}Rn. When ^{218}Po decays, it emits an α-particle with a relatively high energy of 6.12 MeV. With a half life of 3.05 min it is possible that ^{218}Po will emit an α-particle during the time that it resides in the lung. However, its relatively short half life tends to prevent its being easily distributed throughout the body from the lungs.

Threats from ^{214}Pb and ^{214}Bi

Lead-214 and ^{214}Bi are metals with half lives of 26.8 min and 19.7 min, respectively. These two radioisotopes decay by low energy β emission, but are still a threat to human health, although less so than the other short-lived ^{222}Rn progeny that decay by α emission (Fig. 1). Their relatively longer half lives and low energy relegate ^{214}Pb and ^{214}Bi to a slightly lesser threat status. In addition, their half lives are still too short to allow for substantial distribution throughout the body.

Threats from ^{214}Po

Polonium-214 has a very short half life (164 μs). It emits an α-particle with a high energy of 7.69 MeV. With a half life of just 164 μs it is highly likely that ^{214}Po will emit an α-particle during the time that it resides in the lung. Its very short half life and high energy makes ^{214}Po a significant threat to human health. Although the very short half life of ^{214}Po prevents its distribution throughout the body, the relatively long half life of its immediate progeny ^{210}Pb (22.3 yr) can result in serious harm in parts of the body other than the lungs from the decay of ^{210}Pb.

Polonium radionuclides have many of the characteristics of rare-earth elements, are amphoteric, and tend to form hydroxides and radiocolloids *in vitro*[8] and *in vivo*[9]. The latter tends to cause polonium to become phagocytized[10] by cells of the reticuloendothelial system[11] for eventual deposition in the spleen, lymph nodes, bone marrow, liver, and kidneys after parenteral administration[12] (NRC, 1988, p. 161). Fortunately, the half lives of the polonium radionuclides in the immediate ^{222}Rn-decay series are of such a short duration ($T_{1/2}$ for ^{218}Po = 3.05 min and $T_{1/2}$ for ^{214}Po = 164 μs) these problems are generally not a major concern. However, ^{210}Pb with its much longer half life ($T_{1/2}$ = 22.3 yr) is of concern.

HEALTH EFFECT ESTIMATES FROM EXPOSURES TO ^{222}RN AND ITS PROGENY

Inhalation exposure to significant levels of ^{222}Rn and its progeny (assumed to be in equilibrium) have been shown to cause acute and chronic effects on laboratory animals and humans (Table 2 and Fig. 3) (ATSDR, 1990, p. 12–27). However, the processes linking inhalation of ^{222}Rn and its progeny to increased lung cancer risk are complex (ICRP, 1994a, p. 2) primarily because of the numerous confound-

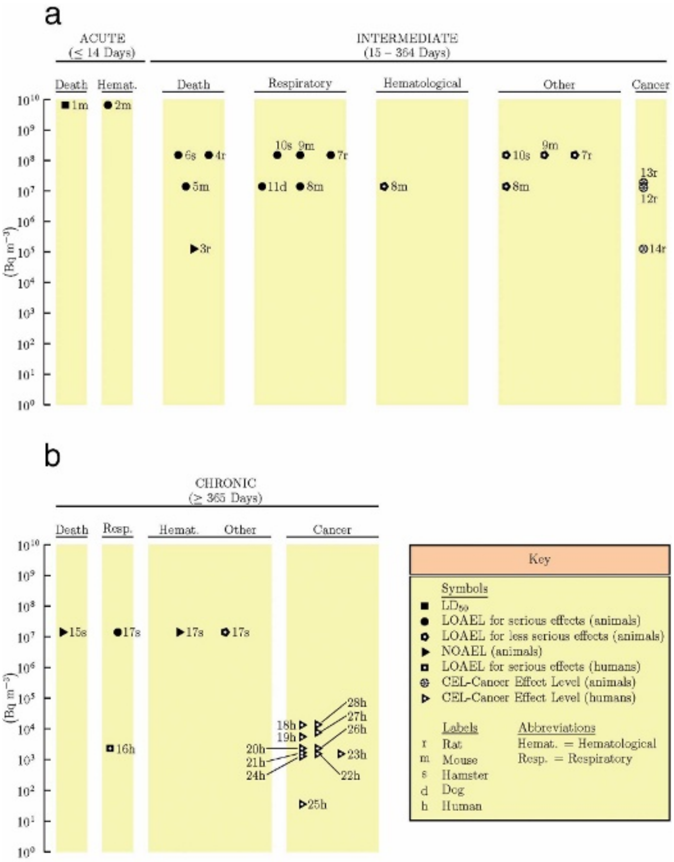

Figure 3. Levels of significant inhalation exposure to ^{222}Rn (modified from ATSDR, 1990, pp. 16–17). Numbers next to each data point correspond to superscripts for each entry in Table 2. Acute and Intermediate effects = a and chronic effects = b.

ing factors[13] (ICRP, 1994a, p. 7) (e.g., smoking). For this reason, many of the epidemiological studies on miners and animals are inadequate so that health research continues.

Review of Selected Animal and Human Studies

The ^{222}Rn concentrations used in the studies cited by ATSDR (1990, p. 12–27) ranged from a low of 56 Bq m^{-3} (human studies) to a high of 8.14 × 10^{9} Bq m^{-3} (animal studies). In the human studies, a cancer effect level in lungs was identified (actual exposure frequency/duration was from >2–30 yr). In the animal studies, mouse mortality and development of hematological (anemia) symptoms occurred after a 30 d Median Lethal Dose (LD_{50}) study (actual exposure frequency/duration was from 5–40 h).

Animal Studies

The mouse studies obviously involved much higher doses of ^{222}Rn than would typically be experienced by a caver (see Table 1), but the exposure time would be comparable. The human study and other similar studies cited by ATSDR (1990) include ^{222}Rn concentrations that a typical caver may be exposed to, but the examined exposure times are generally longer than would be typical for a caver (an exception can be made for tour guides, maintenance workers, etc.).

The animal studies listed in Table 2 resulted in few lung cancers (21% in dogs, zero in mice, and 1.3% in Syrian hamsters) even though the ^{222}Rn doses to which the animals were exposed were extremely high (NRC, 1999, p. 43). Syrian hamsters did not develop any tumors at exposures below 3.89 × 10^{5} J s m^{-3} (3.0 × 10^{4} WLM) whereas rats showed a high incidence of respiratory-tract tumors after exposure to ^{222}Rn. However, according to NRC (1999, p. 43–44) the mechanistic bases of these interspecies differences are such that species-to-species extrapolations of absolute risk cannot be used. As a result, direct extrapolation of animal data to humans cannot be used to predict absolute risk.

Human Studies

Epidemiological studies on the effects of ^{222}Rn gas and its progeny on human health consist primarily of studies on ^{238}U and phosphate miners (^{238}U is associated with phosphate deposits). The human studies, except for the Svensson et al. (1989) study (number 25 in Table 2 and Figure 3), mostly tend to cluster in the cancer region for ^{222}Rn concentrations around 1,000 to 10,000 Bq m^{-3} (Figure 3). These epidemiological studies of cohorts of miners confirm that long-term exposure to high levels of ^{222}Rn gas and its progeny represent a very serious threat to human health.

One human study (Svensson et al., 1989) while suggesting a clear link between ^{222}Rn and small cell carcinoma in the lung, also notes that cancers were less prevalent in the rural cohort over the urbanized cohort where ambient air pollution was a positive confounder. This discrepancy is regarded by the authors as a serious flaw in the study. Additionally, according to Snihs (1973) no conclusions regarding dose and effect below 50 mSv (5 rem) may be drawn because of the large uncertainties and statistical errors. This suggests that the risks to cavers and cave workers from exposure to ^{222}Rn in caves may not be overly significant.

Exposure of Cavers and Cave Workers to ^{222}Rn and its Progeny

The formation of ^{222}Rn and its progeny is shown by the decay sequence in Figure 1. Radon-222 readily migrates to areas with a negative air space, such as caves and tunnels. It is also soluble in water and will reside in cave waters and atmospheres in equilibrium (Fig. 4). In addition, the ^{222}Rn parent, ^{226}Ra, will react with and precipitate on cave walls as $RaCO_3$ and thus provides a continuous source of ^{222}Rn. The net result is that ^{222}Rn concentrations in caves are considerably higher than typically occur in above ground residences, but are significantly less than those found in ^{238}U mines.

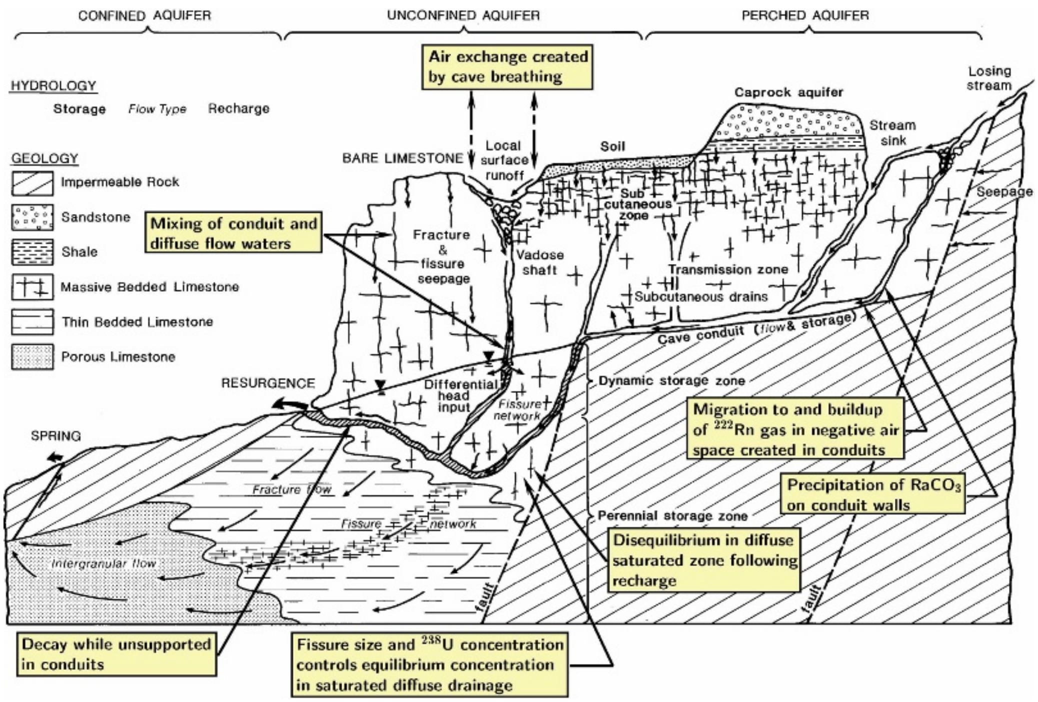

Figure 4. Factors controlling the ingrowth and decay of ^{222}Rn equilibrium activities in a cave system (modified from Smart and Friederich, 1986; Smart, 1991). Radon-222 ingrowth and decay processes in karst aquifer waters provided by Peter Smart (*pers. comm.*). Other important factors include dilution and volatilization. Cave breathing effects on ^{222}Rn concentrations are described in Cunningham and LaRock (1991); Yarborough and Meyers (1978, pp. 22–42. Precipitation of $RaCO_3$ on conduit walls is described in Field (1994, pp. 59–61). Radon-222 secular equilibrium is established after 26 days.

Cumulative Exposure

The decay of ^{222}Rn to its progeny results in secular equilibrium, provided none of its progeny plate out (i.e., adsorb to cave walls). Cumulative exposure C_E has historically been calculated in terms of working levels (WL) with 170 h for a working level month (WLM) and is calculated (in SI units of J h m^{-3}) using (NRC, 1999, p. 178)

$$C_E = \sum_{i=1}^{n} \left(\overline{C}_{Rn}\right)_i \frac{t_i}{170} \tag{3}$$

where $(\overline{C}R_n)_i$ is the average concentration of ^{222}Rn decay products during an exposure interval expressed in J m^{-3} and t_i is the number of hours of the exposure.

The significance to cavers of Equation (3) is the hours of exposure. According to NRC (1999, p. 178), the cumulative exposure for individuals who continuously occupy a residence (commonly known as shut-ins) at a given decay product concentration is greater than four times that for an occupational exposure (8,766 h compared to 2,000 h worked on an annual basis). This means that for cave tour guides who work no more than 170 hours per month will be exposed to one quarter that of individuals who do not leave their dwelling. For recreational caving, exposure will generally be considerably less.

The net result is that individuals living in above ground dwellings, but are not necessarily shut-ins, are annually exposed to 4.8 mSv of ^{222}Rn, as compared to coal and metal miners who are annually exposed to just 0.7 and 2.7 mSv of ^{222}Rn, respectively (Wrixon et al., 2004, p. 40). For cavers and cave workers, radiation doses are likely to be much less because, although ^{222}Rn concentrations in caves are likely to be similar to that of coal mines, they will be lower than in ^{238}U mines while exposure times will typically be much less than that of an occupant of a dwelling.

Comparative Dosimetry

The activity of the ^{222}Rn decay products is described by the Potential Alpha-Energy Concentration (PAEC) which is a non-equilibrium mixture. The PAEC is obtained from the potential alpha energy per unit of activity (Bq) of the considered radionuclide according to $\varepsilon_p/\lambda_r = (\varepsilon_p T_{1/2}/\ln 2)$ (ICRP, 1994a, p. 3). The total airborne PAEC may be obtained from (ICRP, 1994a, p. 4)

$$C_p = \sum_i C_i \left(\frac{\varepsilon_{p,i}}{\lambda_{r,i}}\right) \tag{4}$$

where values for ε_p and λ_r are listed in Table 3. The half life of ^{214}Po is so short ($T_{1/2} = 164$ µs; see Fig. 1) that for all practical purposes it is always in equilibrium with its parent

Table 3. Potential α-energy per atom and per unit activity (modified from ICRP, 1994a, p. 3).

Radionuclide	Half-Life (min)	Potential α-Energy per Atom (MeV)	per Atom (10^{-12} J)	per Unit of Activity, ε_p (MeV Bq^{-1})	per Unit of Activity, ε_p (10^{-10} J Bq^{-1})
^{222}Rn Progeny					
^{218}Po	3.05	13.69	2.19	3,615	5.79
^{214}Pb	26.8	7.69	1.23	17,840	28.6
^{214}Bi	19.9	7.69	1.23	13,250	21.2
^{214}Po	2.73×10^{-6}	7.69	1.23	2.0×10^{-3}	3.0×10^{-6}
Total (at equilibrium), per Bq or ^{222}Rn				34,710	55.6

^{214}Bi and is not needed in the decay chain calculations (NRC, 1999, p. 137). The Potential Alpha-Energy Exposure (PAEE) may then be calculated from (ICRP, 1994a, p. 4)

$$P_p(t) = \int_0^t C_p(t) \tag{5}$$

where time t is expressed as the amount of time an individual is exposed (e.g., one week, one month, etc.).

The equilibrium factor F is defined as the ratio of ^{222}Rn decay product concentration to that of ^{222}Rn and is given by (Hopke et al., 1995)

$$F = \frac{1.18 \times 10^8 \; C_p}{C_{Rn}} \tag{6}$$

where the value of F ranges from 0.2 to 0.8, but typically ranges from 0.35 to 0.40. A default indoor value of 0.4 is recommended by ICRP (1994a, p. 20). However, because of the difficulty of estimating ^{222}Rn decay product concentrations in caves which range from 0.04 to 0.95, a mean value of 0.5 is usually assigned to F for cave studies (see for example, Hyland and Gunn, 1994) although a strong basis for this contention has not been reported. Aley et al. (2006) suggested that, for some notable exceptions, F for most show caves probably ranges between 0.5 and 1.0, although a strong basis for this contention was not supported in this instance either.

Using Equation (6) it is possible to calculate the actual Equilibrium Equivalent Exposure (EEQ) from (ICRP, 1994, P. 4)

$$P_{eq}(t) = \int_0^t C_{eq}(t) \tag{7}$$

where

$$C_{eq} = F \; C_{Rn} \tag{8}$$

The EEQ is a measure of the exposure to ^{222}Rn and its progeny that an individual receives for a given ^{222}Rn concentration. It is the EEQ that determines how seriously an individual has been exposed to a given concentration of ^{222}Rn and its progeny for a given period of time.

RECOMMENDED ^{222}RN EXPOSURES

Allowable exposures to cave workers to PAEC have varied over the years as cancer risks have become better understood. Initial U.S. Government regulations were first set in 1976, but were later revised.

1976 Recommendations

In 1976, the National Institute of Occupational Safety and Health (NIOSH) recognized that ^{222}Rn progeny at several caves managed by the National park Service (NPS) were near the occupational limits as set forth in Occupational Safety and Health Administration (OSHA) standards for ^{238}U miners. NPS caves in which the PAEC exceeded 6.24 μJ m^{-3} (0.30 WL) include Carlsbad Caverns National Park, N.M., Lehman Caves National Monument, Nev., Mammoth Cave National Park, Ky., Oregon Caves National Park, Ore., and Round Spring Cave in Ozark National Scenic Riverways, Mo. Additionally, the PAEC inside the caves and above ground buildings cooled by cave air at Mammoth Cave were 12.48 μJ m^{-3} (0.60 WL) (Baier, 1976). Specific recommendations by NIOSH are shown in Table 4.

Current Recommendations

Current recommended regulations regarding exposures of workers to ^{222}Rn are listed in Tables 5 and 6. The recommendations listed in Table 5 are intended to be conservatively protective. These levels are applicable to cave workers (e.g., tour guides), but are overly restrictive for infrequent cave explorers. According to Strom et al., (1996, p. 5) (citing NCRP, 1993, p. 49) effective dose in the workplace should not exceed 5 cSv (5 rem) in any one year with $A_{ge} \times 1$ cSv as a lifetime limit. If the ICRP (1994a) recommendations are applied, then the the NCRP recommendations convert to 5 cSv (5 rem) in any one year with $A_{ge} \times 7.08$ mJ h m^{-3} or $A_{ge} \times 1$ cSv as a lifetime limit.

Regulations specific to cave workers (and miners) are shown in Table 6. The cave worker regulations were developed and published by OSHA (OSHA, 1988) and Mine Safety and Health Administration (MSHA) (MSHA, 1989). OSHA sets an individual exposure limit equal to 14.0 mJ h m^{-3} = 20.0 mSv yr^{-1} (4.0 WLM yr^{-1}) (OSHA,

Table 4. Recommended regulations by NIOSH for exposure of cavers to ^{222}Rn decay progeny in 1976 (modified from Baier, 1976).

PAEC Level		
(μJ m^{-3})	(WL)	Recommended Regulation
>2.08	>0.1	All-underground smoking stopped
2.08–4.16	0.1–0.2	Monitor workspace at least quarterly
4.16−6.24	0.2–0.3	Monitor workspace quarterly
>6.24	>0.3	Monitor workspace weekly and maintain exposure records on all exposed employees
20.80−41.60	1.0–2.0	Immediate corrective action to lower PAEC below 20.80 μJ m^{-3} (1.0 WL)
>41.60	>2.0	Withdraw all workers not necessary to lower PAEC below 20.80 μJ m^{-3} (1.0 WL)

Cumulative individual exposure shall not exceed 14.0 mJ h m^{-3} yr^{-1} (4.0 WLM yr^{-1}).

1988, 41 CFR §57.5038). MSHA also sets a maximum cumulative dose equal to 14.0 mJ h m^{-3} = 20.0 mSv yr^{-1} (4.0 WLM yr^{-1}) (MSHA, 1989, 30 CFR Part 57). However, ICRP65 was a little more specific in that it set a recommended effective dose at 14.0 mJ h m^{-3} = 20.0 mSv yr^{-1} (4.0 WLM yr^{-1}) averaged over five years and 35.0 mJ h m^{-3} = 50.0 mSv yr^{-1} (10.0 WLM yr^{-1}) in any single year (ICRP, 1994a, p. 21).

Aley et al. (2006) lays out a strategy for reducing total α radiation exposures of show-cave employees to As Low As Reasonably Achievable (ALARA[14]) levels. Although not yet approved in 2006, it is likely that some form of the strategy will be approved by the National Caves Association in which each member will be required to develop a Cave Radiation Management Plan following guidelines developed by OSHA.

DETERMINING ^{222}RN RISKS TO CAVERS

The risks posed by exposure to elevated levels of ^{222}Rn gas have not adequately addressed exposures to recreational cavers and cave workers. Regulations not specific to caves have been promulgated (e.g., MSHA, 2005, §57.5037–§57.5046) while regulations specific to caves have been developed (NPS, 1980) and are being updated (NPS, 2005). These regulations generally specify acceptable Working Levels for individuals, but not exposure rates, absorbed doses, or effective doses which are necessary for determining risks. However, because human health effects caused by elevated ^{222}Rn concentrations are based on epidemiological studies of miners subjected to much higher ^{222}Rn exposures (concentrations and times) as well as confounding factors (smoking, dust, etc.), risk estimates for cavers and cave workers need to be established using the linear no-threshold theory (LNT) even though the associated uncertainty in the cancer risk per unit dose at low dose and dose rate is difficult to quantify (Eckerman et al., 1999, p. 11–12).

APPLICATION OF THE LNT TO ^{222}RN AND ITS PROGENY

The LNT for radiation carcinogenesis is based on the concept that all radiation doses, no matter how small, can cause cancer (i.e., there is no acceptable radiation threshold at which cancers will not be initiated). According to this

Table 5. Recommended regulations by DOE for exposure to ^{222}Rn-decay progeny in 1996 (modified from Strom et al., 1996, p. 6).

	PAEC		PAEE		
Country[a]	(μ J m^{-3})	(WL)	(mJ m^{-3} yr^{-1})	(mSv yr^{-1})	(WLM yr^{-1})
United States	6.93	⅓	14.0	20.0	4.0
Canada, France, Great Britain	8.32	0.4	16.8	24.0	4.8
	…	…	17.5	25.0	5.0[b]
	…	…	35.1	50.0	10.0[c]
	…	…	35.1	50.0	10.0[d]

[a] The United States values are based on U.S. Environmental Protection Agency (EPA), U.S. Department of Energy (DOE), and U.S. Nuclear Regulatory Commission (NRC) regulations.
[b] Values are for any single year — A_{ge} × 3.54 mJ h m^{-3} (A_{ge} × 1 WLM).
[c] Values are for any single year — A_{ge} × 7.08 mJ h m^{-3} (A_{ge} × 2 WLM).
[d] Values are for any single year —14.0 mJ h m^{-3} yr^{-1} (4.0 WLM yr^{-1}) averaged over 5 yr.

Table 6. Published regulations by OSHA and MSHA for exposure of cavers to ^{222}Rn-decay progeny in 1976 (modified from ATSDR, 1990, p. 93–94).

PAEC Level		PAEE Level			
(μJ m^{-3})	(WL)	(mSv yr^{-1})	(WLM yr^{-1})	Published Regulations	Reference
…	…	20.0	4.0	Individual exposure limit	OSHA[a]
2.08	0.1	…	…	Monitor workspace at least once yearly	OSHA[b]
2.08–6.24	0.1–0.3	…	…	Monitor workspace quarterly	OSHA[c]
>6.24	>0.3	…	…	Monitor workspace weekly and maintain exposure records on all exposed employees	OSHA[d]
20.80	1.0	…	…	Immediate corrective action to lower PAEC	OSHA[e]
20.80	1.0	…	…	Instantaneous maximum	MSHA[f]
…	…	20.0	4.0	Maximal cumulative dose	MSHA[f]

[a] (OSHA, 1988, 41 CFR §57.5038).
[b] (OSHA, 1988, 41 CFR §57.5087).
[c] (OSHA, 1988, 41 CFR §57.5037).
[d] (OSHA, 1988, 41 CFR §57.5037).
[e] (OSHA, 1988, 41 CFR §57.5041).
[f] (MSHA, 1988, 30 CFR Part 57).

theory then, if exposure to 1 Gy (100 rad) causes a cancer risk R, the risk from exposure to 10^{-2} Gy (1 rad) is R/100, the risk from exposure to 10^{-5} Gy (1 mrad) is $R/10^5$, and so on, which means that only a zero radiation dose will result in a zero risk of cancer (Cohen, 2002).

Cancer Risk Modeling for exposure to ^{222}Rn and its Progeny

Models intended to address cancer risks from exposure to ^{222}Rn and its progeny have evolved over the years, although all have followed the LNT (Yu et al., 2006). The most current model was developed and published in ICRP66 (ICRP, 1994b).

Human Respiratory Tract Model for Effective Dose Estimation

Using the program Lungdose.F90 (Nikezic and Yu, 2001) which was developed according to the Human Respiratory Tract Model (HRTM), an estimated equilibrium factor F equal to 0.366 was obtained, which closely matches the ICRP65 recommended value (F = 0.4) (ICRP, 1994a, p. 5) and the BEIR VI arithmetic average value of 0.408 (James et al., 2003). An average inhalation rate I_h = 2.16×10^4 m^3 s^{-1} in a residence resulted in an estimated thoracic dose D_T of 79.20 nSv (Bq h m^{-3})$^{-1}$ (126.112 mSv WLM^{-1}). Most interestingly, Lungdose.F90 resulted in an estimate for a Dose Conversion Factor (DCF) equal to 9.50 nSv (Bq h m^{-3})$^{-1}$ (15.13 mSv WLM^{-1}) which is considerably larger than the epidemiological estimate for a DCF equal to 3.18 nSv (Bq h m^{-3})$^{-1}$ (5.06 mSv WLM^{-1}) for workers and 2.44 nSv (Bq h m^{-3})$^{-1}$ (3.88 mSv WLM^{-1}) for the public (ICRP, 1994a, p. 13). This discrepancy emphasizes the complexities and uncertainties when calculating risks posed by exposure to PAEC (Gourmelon et al., 2005, p. 19).

The difference between the Lungdose.F90 estimate for a DCF equal to 9.50 nSv (Bq h m^{-3})$^{-1}$ (15.13 mSv WLM^{-1}) and the ICRP65 estimate for a DCF equal to 3.18 nSv (Bq h m^{-3}) (5.06 mSv WLM^{-1}) is not regarded as significantly large because of the complex physical and biological issues involved and reasonably matches a previously epidemiologically-estimated value of 9.0 nSv (Bq h m^{-3}) $^{-1}$ (14.33 mSv WLM^{-1}) (UNSCEAR, 2000, p. 107). An evaluation of the discrepancy has resulted in the suggestion that the epidemiologically-based estimate for DCF will need to be increased and that for now, the larger DCF value estimated dosimetrically using the HRTM is recommended for use in risk calculations (UNSCEAR, 2000, p. 107). However, others feel that the epidemiologically-based estimates are more scientifically sound (Neal Nelson, *pers. comm.*).

Using the values estimated from Lungdose.F90 developed by Nikezic and Yu (2001) with $I_h = 3.33 \times 10^4$ m^3 s^{-1} to account for a combination of resting, light and heavy exercise (James et al., 2003) typical of caving, the ^{222}Rn concentrations listed in Table 1 and Equation (9) (Wiegand et al., 1995)

$$E_{DA} = C_{Rn}\, F\, T_i\, D_{CF} \tag{9}$$

produced the annual effective doses E_{DA} for ^{222}Rn exposures to recreational cavers (50 h yr^{-1}), professional cavers (600 h yr^{-1}), part-time cave workers (1,760 h yr^{-1}), and full-time cave workers (2,000 h yr^{-1}) (Table 7). Realistically, there is no reliable way to estimate the average number of hours experienced by recreational cavers, professional cavers, and part-time cave workers. The number of caving hours per year for cavers (50 h yr^{-1} and 600 h yr^{-1}) are considered reasonable estimates. Part-time cave worker hours equal to 1,760 h yr^{-1} was used as an estimate because this value is recommended for

Table 7. Estimated annual effective doses using the LUNGDOSE.F90 program[a] for exposures to cavers and cave workers for mean ^{222}Rn concentrations listed in Table 1. Superscript numbers next to each entry correspond to the x-axis on Figures 5–8. Entries without a superscript were not plotted.

	Recreational Caver[b]		Professional Caver[c]		Part-Time Cave Worker[d]		Full-Time Cave Worker[e]	
Country	(mSv yr^{-1})	(WLM yr^{-1})	(mSv yr^{-1})	(WLM yr^{-1})	(mSv yr^{-1})	(WLM yr^{-1})	(mSv yr^{-1})	(WLM yr^{-1})
[1]Australia	0.14	0.03	1.73	0.35	5.07	1.01	5.77	1.15
[2]China[f]	0.03	0.01	0.40	0.08	1.17	0.23	1.33	0.27
[3]Czech Republic	0.29	0.06	3.50	0.70	10.27	2.05	11.67	2.33
[4]Great Britain	0.69	0.14	8.24	1.65	24.18	4.84	27.48	5.50
Great Britain	…	…	…	…	…	…	…	…
[5]Great Britain	8.48	1.70	101.77	20.35	298.53	59.71	339.24	67.85
[6]Great Britain	2.20	0.44	26.39	5.28	77.41	15.48	87.96	17.59
[7]Great Britain	0.09	0.02	1.04	0.21	3.04	0.61	3.45	0.69
[8]Great Britain	0.07	0.01	0.89	0.18	2.62	0.52	2.98	0.60
[9]Greece	5.95	1.19	71.40	14.28	209.44	41.89	238.00	47.60
[10]Hungary	0.78	0.16	9.36	1.87	27.45	5.49	31.19	6.24
[11]Hungary	0.58	0.12	7.00	1.40	20.53	4.11	23.33	4.67
[12]Ireland	0.98	0.20	11.70	2.34	34.33	6.87	39.01	7.80
[13]Japan	$<$ 0.01	$<$ 0.01	0.03	0.01	0.09	0.02	0.10	0.02
[14]Malaysia	0.14	0.03	1.69	0.34	4.96	0.99	5.63	1.13
[15]Poland	0.28	0.06	3.31	0.66	9.70	1.94	11.02	2.20
[16]Russia	0.56	0.11	6.78	1.36	19.88	3.98	22.59	4.52
[17]Slovenia	0.33	0.07	4.00	0.80	11.75	2.35	13.35	2.67
[18]Slovenia	0.23	0.05	2.74	0.55	8.03	1.61	9.12	1.82
[19]Spain	0.03	0.01	0.31	0.06	0.90	0.18	1.02	0.20
[20]Spain	0.84	0.17	10.11	2.02	29.65	5.93	33.69	6.74
[21]South Africa	0.06	0.01	076	0.15	2.22	0.44	2.52	0.50
[22]Switzerland	5.91	1.18	70.89	14.18	207.95	41.59	236.31	47.26
[23]United States	0.46	0.09	5.46	1.09	16.03	3.21	18.21	3.64
[24]United States	0.61	0.12	7.34	1.47	21.54	4.31	24.47	4.89
[25]United States	0.35	0.07	4.18	0.84	12.27	2.45	13.94	2.79
United States	…	…	…	…	…	…	…	…
[26]United States	2.76	0.55	33.12	6.62	97.14	19.43	110.38	22.08

[a] Lungdose.F90 program (Nikezik and Yu, 2001) estimate for DCF = 12.92 nSv (Bq h m^{-3})$^{-1}$ (20.75 mSv WLM^{-1}) and D_T = 107.63 nSv (Bq h m^{-3})$^{-1}$ (171.38 mSv WLM^{-1}) for $I_h = 3.33 \times 10^{-4}$ m^3 s^{-1}.
[b] Recreational cavers = 50 h yr^{-1} of caving.
[c] Professional cavers = 600 h yr^{-1} of caving.
[d] Part-time cave worker = 1,760 h yr^{-1} of cave work.
[e] Full-time cave worker = 2,000 h yr^{-1} of cave work.
[f] The measured ^{222}Rn concentrations for the China data listed in Table 1 are better represented by 7,000 h yr^{-1} exposure with an $I_h = 2.16 \times 10^{-4}$ m^3 s^{-1} because these data are from cave dwellings resulting in an E_{DA} = 3.43 mSv yr^{-1} (0.69 WLM yr^{-1}).

outside exposure by UNSCEAR (2000, p. 107), even though UNSCEAR recommended a larger equilibrium factor of (0.6) for external exposures, but which was not used in the calculations because it is not appropriate for caves.

An $I_h = 3.33 \times 10^4$ m^3 s^{-1} resulted in a greater D_T and a greater overall E_{DA} for cavers and cave workers than when an $I_h = 2.16 \times 10^4$ m^3 s^{-1} was used because of the much greater breathing activity. Mean annual effective doses E_{DA} listed in Table 7 typically ranged from much less (0.03 mSv yr^{-1}) to much greater (339.27 mSv yr^{-1}) than the recommended maximums of 20 to 50 mSv yr^{-1}. Unfortunately, the great range of data and variability evidenced make it very difficult to realistically estimate the risks posed to cavers and cave workers from the estimated E_{DA}. However, it appears from Table 7 that recreational cavers and, for the most part, professional cavers are likely to be only minimally exposed to excess ^{222}Rn concentrations whereas cave workers should be more concerned about exposure to excess ^{222}Rn concentrations for the five countries with high mean ^{222}Rn concentrations (Great Britain, Greece, Japan, Switzerland, and the United States) (Table 7).

Figures 5–8 illustrate the threat to cavers and cave workers from exposure to elevated levels of ^{222}Rn gas in caves relative to acceptable limits. From Figures 5–8 it is

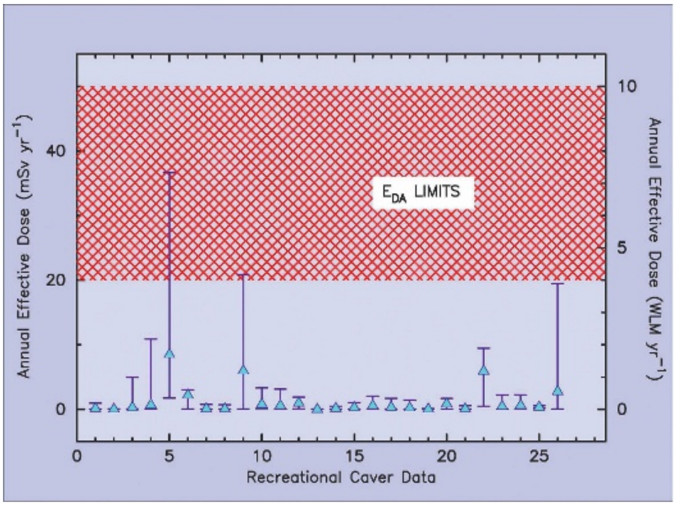

Figure 5. Plot of mean, minimum, and maximum annual effective dose values for recreational cavers from Table 7 relative to published acceptable limits of 20−50 mSv yr^{-1} (4−10 WLM yr^{-1}). The x-axis numerical values correspond to the superscript labels in Table 7. (Note that data sets listed in Table 7 missing mean values [Great Britain and United States] are not plotted).

apparent that cavers are generally not at risk while cave workers appear to be minimally at risk.

A series of notched boxplots (see Chambers et al., 1983, for a description of notched boxplots) using the data listed in Table 7 and shown in Figure 9 further demonstrate that only cave workers will be minimally impacted at the lower E_{DA} limit of 20 mSv yr^{-1} (4 WLM yr^{-1}). However, the median line of each notched boxplot for the part-time and full-time cave workers are also below the minimum acceptable limit for exposure, suggesting that neither the part-time nor the full-time cave workers are impacted at the lower E_{DA} limit, and only the the more extreme values

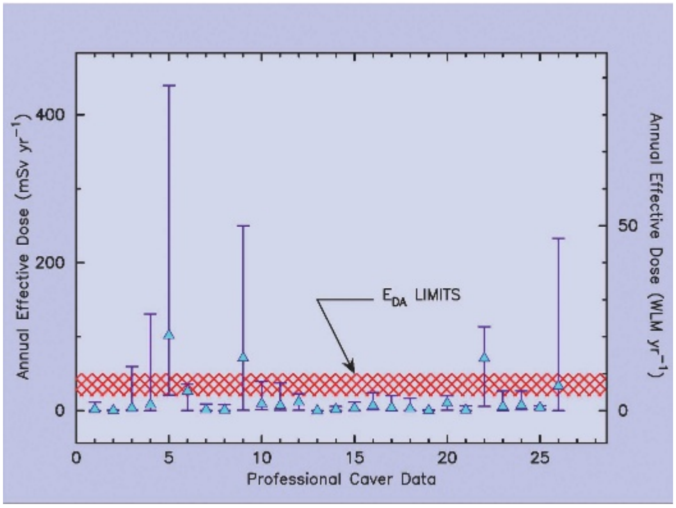

Figure 6. Plot of mean, minimum, and maximum annual effective dose values for professional cavers from Table 7 relative to published acceptable limits of 20–50 mSv yr−1 (4–10 WLM yr^{-1}). The x-axis numerical values correspond to the superscript labels in Table 7. (Note that data sets listed in Table 7 missing mean values [Great Britain and United States] are not plotted).

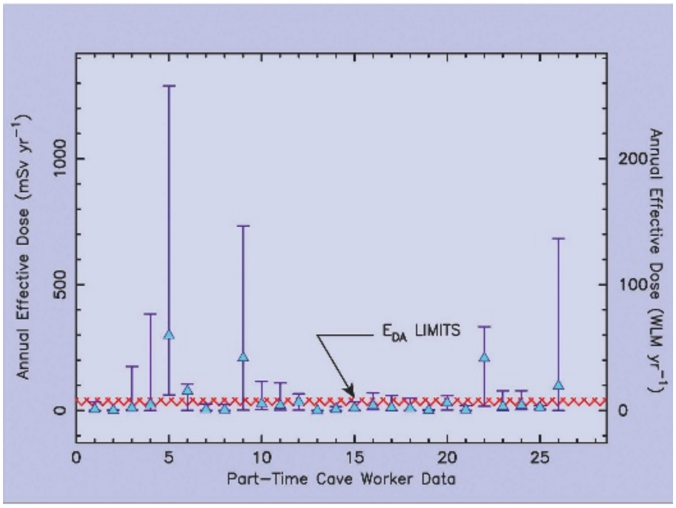

Figure 7. Plot of mean, minimum, and maximum annual effective dose values for part-time cave workers from Table 7 relative to published acceptable limits of 20–50 mSv yr^{-1} (4–10 WLM yr^{-1}). The x-axis numerical values correspond to the superscript labels in Table 7. (Note that data sets listed in Table 7 missing mean values [Great Britain and United States] are not plotted).

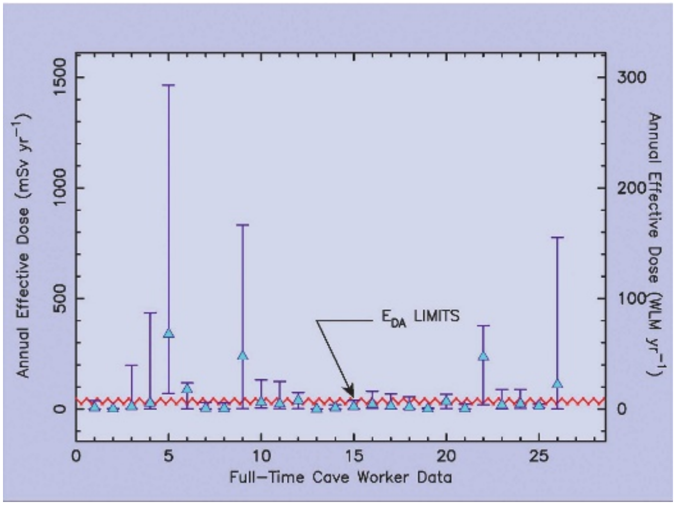

Figure 8. Plot of mean, minimum, and maximum annual effective dose values for full-time cave workers from Table 7 relative to published acceptable limits of 20–50 mSv yr^{-1} (4–10 WLM yr^{-1}). The x-axis numerical values correspond to the superscript labels in Table 7. (Note that data sets listed in Table 7 missing mean values [Great Britain and United States] are not plotted).

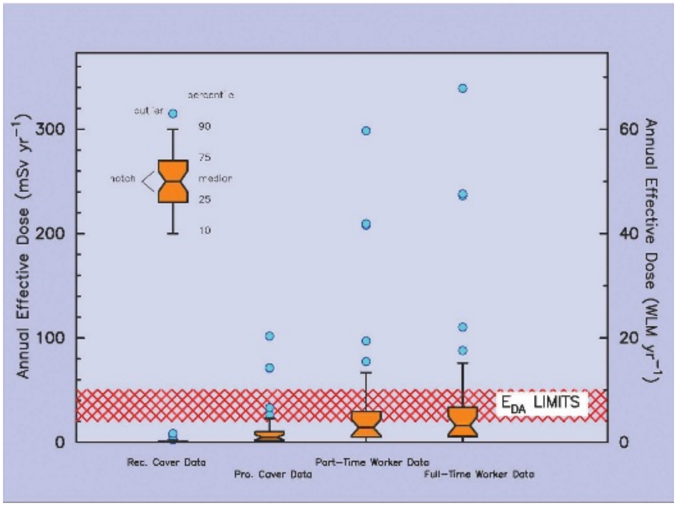

Figure 9. Notched boxplots of estimated annual effective doses relative to acceptable limits. (Note that data sets listed in Table 7 missing mean values [Great Britain and United States] are not plotted).

(i.e., >90th percentile) exceed the 50 mSv yr^{-1} (10 WLM yr^{-1}) limit.

Exposure of Cavers to ^{222}Rn and its Progeny. Exposure of cave workers and cavers to ^{222}Rn and its progeny is obtained from (Eckerman et al., 1999, p. F4)

$$P_{eq}(t) = C_i \int_0^t e^{(-\ln 2t)/T_{1/2}} \tag{10}$$

which considers the decay series of ^{222}Rn through its progeny, of which only the principal progeny identified in Figure 1 are used in the calculations. Each progeny concentration is estimated from the concentration of its respective parent. According to the nuclear decay data listed in Eckerman et al. (1999, p. G19–G20), each radionuclide for the ^{222}Rn decay series decays to between 99.98% and 100% to its principal progeny (e.g., 99.98% of ^{218}Po decay results in ^{214}Pb) (Table 8), which renders insignificant the other progeny shown in Figure 1 (e.g., ^{218}AT and ^{218}Rn).

Applying Equation (10) allows for exposures to cavers from ^{222}Rn and its progeny to be estimated from the ^{222}Rn concentrations listed in Table 1. Estimated exposures are listed in Table 9, where it may be noted that the smallest estimated exposure is produced by ^{214}Po. This appears contrary to the notion that the very short half life of ^{214}Po ($T_{½}$ = 164 μs) will result in the greatest lung doses because ^{214}Po will likely emit an α-particle before it can be exhaled. Polonium-214 decays only once, but is in secular equilibrium with its parent radionuclide ^{214}Bi. However, ^{214}Po has the greatest number of decays per unit intake of ^{222}Rn in equilibrium with its progeny. Its half life, therefore, is not a factor (N. Nelson, pers. comm.).

Risks to Cavers from Exposure to ^{222}Rn and its Progeny. Risks to cave workers and cavers need to be estimated from the exposures listed in Table 9 and risk coefficients determined from epidemiological studies when available. Risks include both mortality and morbidity.

The risks of mortality (cancer death) and morbidity (cancer with or without death) from exposure to ^{222}Rn and its progeny are estimated from (Eckerman et al., 1999, p. F-8)

$$R_{M_i} = P_{eq_i} \, S_C \, I_h \, M_{R_i} \tag{11}$$

where a scaling coefficient S_C of 1.11 for inhalation was considered appropriate (Eckerman et al., 1999, p. E-5) and the values for the mortality[15] and morbidity[16] risk coefficients M_{R_i} are listed in Table 10.

The EPA estimates mortality risks from exposure to ^{222}Rn gas as a function of WLM; specifically, EPA expects 5.4×10^{-4} lung cancer deaths per WLM. This methodology was not used here because the WLM does not account for such factors as breathing rates, tidal volumes, or the fraction of progeny unattached to aerosols, which modify the relationship between exposure and risk (Cothern, 1987, p. 26).

Morbidity risks to cavers and cave workers can not be directly calculated because the relevant morbidity risk coefficients exist only for ^{214}Pb and ^{214}Bi (Table 10). The difference between the mortality and morbidity coefficients for ^{214}Pb and ^{214}Bi are relatively insignificant, but the same cannot be said for the other radionuclides listed in Table 10. In general, it is reasonable to expect that the risk of morbidity to cavers and cave workers will be somewhat greater than is the estimated risk for mortality.

In order to develop a rough estimate for the risk of morbidity for cavers and cave workers, the values for the

Table 8. Nuclear decay products and fractions for ^{222}Rn and its progeny (modified from Eckerman et al., 1999, p. G19–G20).

Radionuclide	$T_{½}$	Decay Mode	Radioactive Decay Products and Fractional Yield			
			Radionuclide	Fraction	Radionuclide	Fraction
^{222}Rn	3.8325 d	α	^{218}Po	1.0000	…	…
^{218}Po	3.05 min	α β−	^{214}Pb	0.9998	^{218}At	0.0002
^{214}Pb	26.8 min	β−	^{214}Bi	1.0000	…	…
^{214}Bi	19.9 min	α β−	^{214}Po	0.9998	^{210}Tl	0.0002
^{214}Po	164.3 μs	α	^{210}Pb	1.0000	…	…

Table 9. Estimated time-integrated concentration exposures to ^{222}Rn and its progeny for cavers for the mean ^{222}Rn concentrations listed in Table 1[a].

Country	Inhalation Exposure				
	^{222}Rn ($Bq\ s^{-1}\ m^{-3}$)	^{218}Po ($Bq\ s^{-1}\ m^{-3}$)	^{214}Pb ($Bq\ s^{-1}\ m^{-3}$)	$Z^{14}Bi$ ($Bq\ s^{-1}\ m^{-3}$)	^{214}Po ($Bq\ s^{-1}\ m^{-3}$)
Australia	4.82×10^{7}	3.35×10^{4}	3.35×10^{4}	3.35×10^{4}	5.58×10^{-4}
China	1.11×10^{7}	7.74×10^{3}	7.74×10^{3}	7.74×10^{3}	1.29×10^{-4}
Czech Republic	9.76×10^{7}	6.78×10^{4}	6.78×10^{4}	6.78×10^{4}	1.13×10^{-3}
Great Britain	2.30×10^{8}	1.60×10^{5}	1.59×10^{5}	1.59×10^{5}	2.66×10^{-3}
Great Britain	…	…	…	…	…
Great Britain	2.84×10^{9}	1.97×10^{6}	1.97×10^{6}	1.97×10^{6}	3.28×10^{-2}
Great Britain	7.35×10^{8}	5.11×10^{5}	5.11×10^{5}	5.11×10^{5}	8.51×10^{-3}
Great Britain	2.88×10^{7}	2.00×10^{4}	2.00×10^{4}	2.00×10^{4}	3.34×10^{-4}
Great Britain	2.49×10^{7}	1.73×10^{4}	1.73×10^{4}	1.73×10^{4}	2.88×10^{-4}
Greece	1.99×10^{9}	1.38×10^{6}	1.38×10^{6}	1.38×10^{6}	2.30×10^{-2}
Hungary	2.61×10^{8}	1.81×10^{5}	1.81×10^{5}	1.81×10^{5}	3.02×10^{-3}
Hungary	1.95×10^{8}	1.35×10^{5}	1.35×10^{5}	1.35×10^{5}	2.26×10^{-3}
Ireland	3.26×10^{8}	2.26×10^{5}	2.26×10^{5}	2.26×10^{5}	3.77×10^{-3}
Japan	8.69×10^{5}	6.04×10^{2}	6.04×10^{2}	6.04×10^{2}	1.01×10^{-5}
Malaysia	4.71×10^{7}	3.27×10^{4}	3.27×10^{4}	3.27×10^{4}	5.45×10^{-4}
Poland	9.21×10^{7}	6.40×10^{4}	6.40×10^{4}	6.40×10^{4}	1.07×10^{-3}
Russia	1.89×10^{8}	1.31×10^{5}	1.31×10^{5}	1.31×10^{5}	2.19×10^{-3}
Slovenia	1.12×10^{8}	7.75×10^{4}	7.75×10^{4}	7.75×10^{4}	1.29×10^{-3}
Slovenia	7.63×10^{7}	5.30×10^{4}	5.29×10^{4}	5.29×10^{4}	8.82×10^{-4}
Spain	8.53×10^{6}	5.93×10^{3}	5.93×10^{3}	5.93×10^{3}	9.87×10^{-5}
Spain	2.82×10^{8}	1.96×10^{5}	1.96×10^{5}	1.96×10^{5}	3.26×10^{-3}
South Africa	2.11×10^{7}	1.47×10^{4}	1.46×10^{4}	1.46×10^{4}	2.44×10^{-4}
Switzerland	1.98×10^{9}	1.37×10^{6}	1.37×10^{6}	1.37×10^{6}	2.29×10^{-2}
United States	1.52×10^{8}	1.06×10^{5}	1.06×10^{5}	1.06×10^{5}	1.76×10^{-3}
United States	2.05×10^{8}	1.42×10^{5}	1.42×10^{5}	1.42×10^{5}	2.37×10^{-3}
United States	1.17×10^{8}	8.09×10^{4}	8.09×10^{4}	8.09×10^{4}	1.35×10^{-3}
United States	…	…	…	…	…
United States	9.23×10^{8}	6.41×10^{5}	6.41×10^{5}	6.41×10^{5}	1.07×10^{-2}

[a] Only the mean time-integrated concentration exposures are shown here. Maximum and minimum exposure values were calculated from the maximum and minimum ^{222}Rn concentrations listed in Table 1 but are not shown here due to space limitations.

morbidity risk coefficient M_{R_B} for ^{214}Pb and ^{214}Bi were taken from Table 10. For the other radionuclides, the mortality risk coefficients M_{R_T} listed in Table 10 were increased by a factor of 1.5 on the assumption that such an increase will reasonably represent a morbidity risk coefficient M_{R_B} for those radionuclides for which morbidity risk coefficients are not yet available.

Table 10. Mortality and morbidity risk coefficients for ^{222}Rn and its progeny.

Radionuclide	Risk Coefficients	
	Motality (Bq^{-1})	Morbidity (Bq^{-1})
^{222}Rn[a]	3.21×10^{-11}	…
^{218}Po[a]	9.44×10^{-11}	…
^{214}Pb[b]	9.31×10^{-10}	9.81×10^{-10}
^{214}Bi[c]	7.45×10^{-10}	7.84×10^{-10}
^{214}Po[a]	7.12×10^{-17}	…

[a] Risk coefficients source: Puskin and Nelson (1994, p. 53).
[b] Risk coefficients source: Eckerman et al. (1999, p. 71).
[c] Risk coefficients source: Eckerman et al. (1999, p. 72).

Mortality and morbidity risks (Table 11) were averaged over all ages and both genders for a population with specified mortality and morbidity for the mean exposures listed in Table 9. The mean risks of mortality and morbidity ranged from 10^{-5} (1 in 100,000) to 10^{-7} (1 in 10,000,000) where 10^{-6} (1 in 1,000,000) is usually considered an acceptable risk.

The significance of the mortality and morbidity inhalation risks posed to cavers and cave workers is shown in Figures 10 and 11. It will be noted from Figures 10 and 11 that the majority of the mean values are very close to the 10^{-6} acceptable risk level, but the maximum measured risks appear considerably greater than the 10^{-6} acceptable risk level. Only data sets represented by numbers 5 (Great Britain), 6 (Great Britain), 9 (Greece), 22 (Switzerland), and 26 (United States) exhibited mean values substantially greater than the 10^{-6} acceptable risk level.

Table 11. Inhalation risks from ^{222}Rn and its progeny for exposures to cavers and cave workers for the ^{222}Rn concentrations listed in Table 1. Superscript numbers next to each entry corresponds to the x-axis on Figures 10 and 11. Entries without a superscript were not plotted.

Country	Inhalation Motality Risk			Inhalation Morbidity Risk		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum
^{1}Australia	5.9×10^{-7}	3.9×10^{-6}	8.8×10^{-9}	8.8×10^{-7}	5.9×10^{-6}	1.3×10^{-8}
^{2}China	1.4×10^{-7}	2.7×10^{-7}	3.7×10^{-8}	2.0×10^{-7}	4.0×10^{-7}	5.5×10^{-8}
^{3}Czech Republic	1.2×10^{-6}	2.0×10^{-5}	1.9×10^{-7}	1.8×10^{-6}	3.0×10^{-5}	2.9×10^{-7}
^{4}Great Britain	2.8×10^{-6}	4.5×10^{-5}	9.7×10^{-9}	4.2×10^{-6}	6.7×10^{-5}	1.4×10^{-8}
Great Britain	…	1.5×10^{-4}	9.7×10^{-8}	…	2.2×10^{-4}	1.4×10^{-7}
^{5}Great Britain	3.5×10^{-5}	1.5×10^{-4}	7.2×10^{-6}	5.2×10^{-5}	2.2×10^{-4}	1.1×10^{-5}
^{6}Great Britain	9.1×10^{-6}	1.2×10^{-5}	6.6×10^{-8}	1.3×10^{-5}	1.8×10^{-5}	9.8×10^{-8}
^{7}Great Britain	3.6×10^{-7}	3.1×10^{-6}	2.5×10^{-8}	5.3×10^{-7}	4.6×10^{-6}	3.8×10^{-8}
^{8}Great Britain	3.1×10^{-7}	3.0×10^{-6}	3.3×10^{-8}	4.6×10^{-7}	4.4×10^{-6}	4.9×10^{-8}
^{9}Greece	2.5×10^{-5}	8.6×10^{-5}	1.8×10^{-7}	3.6×10^{-5}	1.3×10^{-4}	2.7×10^{-7}
^{10}Hungary	3.2×10^{-6}	1.4×10^{-5}	4.9×10^{-7}	4.8×10^{-6}	2.0×10^{-5}	7.2×10^{-7}
^{11}Hungary	2.4×10^{-6}	1.3×10^{-5}	1.9×10^{-7}	3.6×10^{-6}	1.9×10^{-5}	2.9×10^{-7}
^{12}Ireland	4.0×10^{-6}	7.7×10^{-6}	1.9×10^{-7}	6.0×10^{-6}	1.1×10^{-5}	2.9×10^{-7}
^{13}Japan	1.1×10^{-5}	1.9×10^{-8}	7.2×10^{-10}	1.6×10^{-8}	2.9×10^{-8}	1.1×10^{-9}
^{14}Malaysia	5.8×10^{-7}	1.9×10^{-6}	9.7×10^{-8}	8.6×10^{-7}	2.9×10^{-6}	1.4×10^{-7}
^{15}Poland	1.1×10^{-6}	4.1×10^{-6}	5.8×10^{-8}	1.7×10^{-6}	6.0×10^{-6}	8.7×10^{-8}
^{16}Russia	2.3×10^{-6}	8.3×10^{-6}	3.6×10^{-7}	3.5×10^{-6}	1.2×10^{-5}	5.4×10^{-7}
^{17}Slovenia	1.4×10^{-6}	7.0×10^{-6}	1.5×10^{-8}	2.0×10^{-6}	1.0×10^{-5}	2.2×10^{-8}
^{18}Slovenia	9.4×10^{-7}	5.8×10^{-6}	5.8×10^{-8}	1.4×10^{-6}	8.6×10^{-6}	8.7×10^{-8}
^{19}Spain	1.1×10^{-7}	4.8×10^{-7}	4.9×10^{-9}	1.6×10^{-7}	7.1×10^{-7}	7.2×10^{-9}
^{20}Spain	3.5×10^{-6}	6.9×10^{-6}	1.8×10^{-7}	5.2×10^{-6}	1.0×10^{-5}	2.7×10^{-7}
^{21}South Africa	2.6×10^{-7}	2.3×10^{-6}	2.9×10^{-9}	3.9×10^{-7}	3.4×10^{-6}	4.3×10^{-9}
^{22}Switzerland	2.4×10^{-5}	3.9×10^{-5}	1.9×10^{-6}	3.6×10^{-5}	5.8×10^{-5}	2.9×10^{-6}
^{23}United States	1.9×10^{-6}	9.1×10^{-6}	3.6×10^{-8}	2.8×10^{-6}	1.4×10^{-5}	5.4×10^{-8}
^{24}United States	2.5×10^{-6}	9.2×10^{-6}	3.6×10^{-7}	3.7×10^{-6}	1.4×10^{-5}	5.4×10^{-7}
^{25}United States	1.4×10^{-6}	2.3×10^{-6}	7.3×10^{-7}	2.1×10^{-6}	3.4×10^{-6}	1.1×10^{-6}
United States	…	1.8×10^{-6}	3.2×10^{-7}	…	2.7×10^{-6}	4.8×10^{-7}
^{26}United States	1.1×10^{-5}	8.0×10^{-5}	1.1×10^{-8}	1.7×10^{-5}	1.2×10^{-4}	1.6×10^{-8}

Risks were estimated for the mean, maximum, and minimum ^{222}Rn concentrations listed in Table 1 even though exposures for the maximum and minimum ^{222}Rn concentrations are not shown in Table 9.
Label numbers refer to data position in Figures 10 and 11.

Figure 12 shows a set of notched boxplots for the mortality and morbidity inhalation risks. From Figure 12 it can be seen that the median measure of the mean risk values is only slightly greater than the 10^{-6} acceptable risk level, but the notches extend to the 10^{-6} acceptable risk level, suggesting that the overall risks may be acceptable. However, in individual caves and locations within certain caves, risks may be significant, as evidenced by the fact that the 75th percentile, the 90th percentile, and various outliers extend well beyond the 10^{-6} acceptable risk level.

DISCUSSION AND CONCLUSIONS

Attempts have been made to regulate exposures to cavers and cave workers to excess levels of ^{222}Rn gas in caves ever since high levels of ^{222}Rn gas were discovered in some caves administered by the NPS (Yarborough and Meyers, 1978, p. 19). Protection levels for cave workers were implemented at the earliest possible time (Baier, 1976) and have continued to evolve as more is learned. Unfortunately, little is still known about the effects of low-level ionizing α radiation from ^{222}Rn and its progeny. Still, it is widely recognized that the development of lung cancers may be expected based on numerous animal studies and epidemiological studies of miners.

Measuring ^{222}Rn is of little value unless these concentrations are converted to risk estimates. Calculating annual effective doses (mSv yr^{-1} or WLM yr^{-1}) is the generally accepted method for determining human-health threats. Using appropriate limits (20 mSv yr^{-1} to 50 mSv yr^{-1}) helps to put the calculated values in a health-risk context.

In general, it would seem that recreational and professional cavers are minimally at risk of developing lung cancers from exposure to ^{222}Rn, part-time cave workers are

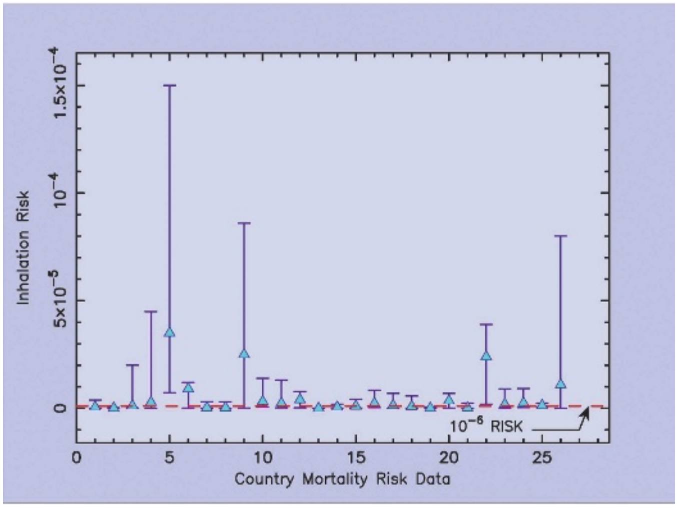

Figure 10. Plot of mean, minimum, and maximum mortality risk values from Table 11 relative to a 10^{-6} acceptable risk. The x-axis numerical values correspond to the superscript labels in Table 11. (Note that data sets listed in Table 11 missing mean values [Great Britain and United States] are not plotted).

somewhat more at risk in some caves, and full-time cave workers more so (Table 7). This conclusion was similarly obtained by Craven and Smit (2006) for non-smokers. Unfortunately, the large degree of uncertainty associated with the calculations and potential discrepancies in the ^{222}Rn measurements, necessitate that the calculations listed in Table 7 be viewed with some degree of skepticism (it is not possible to determine if the calculated annual effective

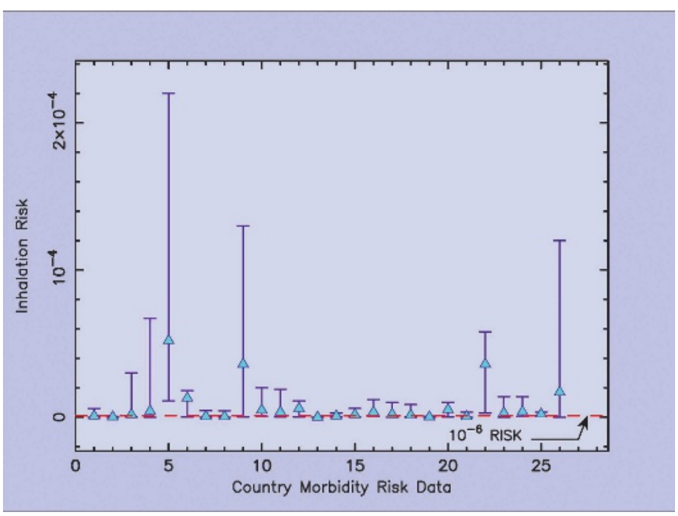

Figure 11. Plot of mean, minimum, and maximum morbidity risk values from Table 11 relative to a 10^{-6} acceptable risk. The x-axis numerical values correspond to the superscript labels in Table 11. (Note that data sets listed in Table 11 missing mean values [Great Britain and United States] are not plotted).

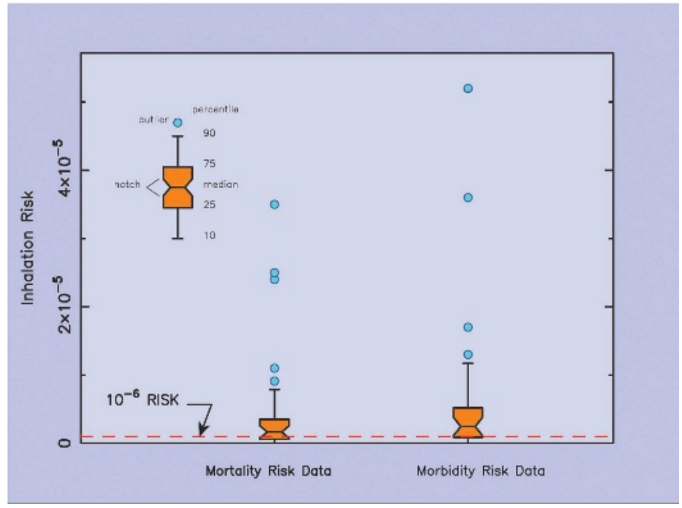

Figure 12. Notched boxplots of estimated mortality and morbidity risks relative to a 10^{-6} acceptable risk. (Note that data sets listed in Table 11 missing mean values [Great Britain and United States] are not plotted).

doses in Table 7 are too high or too low or by how much). However, the annual effective doses listed in Table 7 should still be viewed as representative of the potential risks cavers and cave workers might be subject to when spending any significant amount of time underground.

A less common method of calculating risks posed by low-level ionizing α radiation from ^{222}Rn and its progeny, but which is a more typical method of calculating risks in general, is to use cancer slope factors (mortality and morbidity risk coefficients M_{R_i}) to produce dimensionless risk estimates. The mortality and morbidity risk estimates listed in Table 11 for the ^{222}Rn concentrations listed in Table 1 are of negligible concern.

For short-term exposures, typical of recreational cavers, the risk levels listed in Table 11 for the mean ^{222}Rn concentrations are probably of little concern. The same is probably true for professional cavers. However, for long-term exposures, typical of cave workers, these risk levels warrant some degree of minor concern especially in areas of poor ventilation (Kobal et al., 1988). If the maximum ^{222}Rn concentrations listed in Table 1 are considered, the risks will increase slightly, which may warrant a greater concern.

Overall, it appears that risks to cavers and cave workers are generally low, but in selected caves risks to cave workers may be significant. However, proper cave worker precautions for caves with elevated ^{222}Rn concentrations will minimize the risks. In addition, given the uncertainties associated with use of the LNT, concerns over risks to cave workers may need to depend on the eventual improvements or abandonment of the LNT. Changes to the LNT may result in a reduction or increase in the estimated risks to cavers and cave workers from exposure to elevated levels of ^{222}Rn. Other uncertainties, such as extreme seasonal

Table 12. ^{222}Rn progeny current and historic names.

Current		Historic	
Symbol	Name	Symbol	Name
^{218}Po	Polonium-218	RaA	Radium A
^{214}Pb	Lead-214	RaB	Radium B
^{214}Bi	Bismouth-214	RaC	Radium C
^{214}Po	Polonium-214	RaC′	Radium C′
^{210}Tl	Thallium-210	RaC″	Radium C″
^{210}Pb	Lead-210	RaD	Radium D
^{210}Bi	Bismuth-210	RaE	Radium E
^{210}Po	Polonium-210	RaF	Radium F

variations in measured ^{222}Rn concentrations (Yarborough and Meyers, 1978, p. 22) [e.g. 740 versus 22,165 Bq m^{-3} in Magic Garden, Postojna Cave (Kobal et al., 1988)], further complicate risk calculations.

APPENDIX

RADON-222 PROGENY AND HISTORIC NAMES

When first discovered, the current ^{222}Rn progeny were known as decay products of ^{226}Ra and were formerly designated as Radium A – Radium F. The ^{222}Rn progeny are now known to be the isotopes listed in Table 12.

RADIATION SI UNITS AND CONVERSION TO TRADITIONAL UNITS

Radiation units have evolved over the years. As a result, radiation units can be quite confusing. To alleviate some of the confusion, selected radiation parameters are identified in Table 13 along with the SI special name, symbol, SI derived units, and traditional units.

ACKNOWLEDGMENTS

The author would like to thank Dr. Dragoslav Nikesic for providing me with his program LUNGDOSE.F90 after convert-

Table 13. International System (SI) units and equivalents for traditional units (modified from Taylor, 2001, 1995; Nero, 1988, p. 39).

	SI Derived Unit				
Parameter	Special Name	Special Symbol	Expressed in Terms of Other SI Units	Expressed in Terms of SI Base Units	Conversion for traditional Unit
Activity	becquerel	Bq		s^{-1}	1 Ci = 3.7 × 10^{10} Bq (1 pCi = 0.037 Bq)
Concentration		Bq m^{-3}			1 pCi L^{-1} = 37 Bq m^{-3}
PAEC[a]		J m^{-3}			1 WL = 1.3 × 10^{8} MeV m^{-3} = 2.08 × 10^{-5} J m^{-3}
EEDC[b]		Bq m^{-3}			1 WL PAEC = 3740 Bq m^{-3}
Exposure		J s m^{-3}			1 WLM = 12.97 J s m^{-3} = 3.60 × 10^{-3} J h m^{-3}
Exposure		Bq s m^{-3}			1 WLM = 73.9 Bq yr m^{-3}
Exposure Rate		J m^{-3}			1 WLM yr^{-1} = 4.11 × 10^{-7} J m^{-3}
Exposure Rate		Bq m^{-3}			1 WLM yr^{-1} = 73.9 Bq m^{-3}
Absorbed Dose	gray	Gy	J kg^{-1}	m^{2} s^{-2}	1 rad = 1 cGy = 10^{-2} Gy
Absorbed Dose Rate		Gy s^{-1}		m^{2} s^{-2}	1 rad s^{-1} = 10^{-2} Gy s^{-1}
Dose Equivalent[c]	sievert	Sv	J kg^{-1}	m^{2} s^{-2}	1 rem = 1 cSv = 10^{-2} Sv = 10^{-2} J kg^{-1}
Effective Dose		J s m^{-3}			1 WLM yr^{-1} = 5 mSv yr^{-1}

[a] Potential Alpha-Energy Concentration (PAEC).
[b] Equilibrium-Equivalent Decay-Product Concentration (EEDC).
[c] Also known as Biologically Effective Dose.

ing relevant portions to English. This program has been essential to the understanding of ^{222}Rn risks to cavers. The author would also like to thank Ms. Lindsey Bender and Dr. Neal Nelson of the U.S. Environmental Protection Agency's Office of Radiation and Indoor Air for their support and guidance and for providing specific radiation risk guidance materials. Lastly, the author thanks Dr. Neal Nelson and Dr. Ivan Kobal of the Jožef Stefan Institute (Ljubljana, Slovenia) for their critical reading of the manuscript.

NOTATION

A_{ge}	age of an exposed individual (dimen.)
C_{eq}	EEDC — ^{222}Rn concentration that would result if $F = 1$
C_E	cumulative exposure (J h m^{-3})
C_i	activity concentrations for ^{222}Rn and its progeny (Bq m^{-3})
C_p	PAEC — total α-particle energy potentially emitted by any mixture of ^{222}Rn per unit volume of air (J m^{-3})
$(\overline{C}R_n)_i$	average concentration of ^{222}Rn decay products during exposure interval (J m^{-3})
C_{Rn}	^{222}Rn concentration (Bq m^{-3})
D_{CF}	Dose Conversion Factor
$D_{T,R}$	mean absorbed radiation dose to tissue T from radiation R (Gy)
E_{DA}	annual effective radiation dose to organs and tissues (Sv yr^{-1})
E_D	effective radiation dose to organs and tissues (Sv)
F	equilibrium factor (dimen.)
H_T	human equivalent radiation dose to tissue T (Sv)
I_h	inhalation rate (m^3 s^{-1})
M_{R_B}	morbidity-risk coefficient for ^{222}Rn and its progeny (Bq^{-1})
M_{R_T}	mortality-risk coefficient for ^{222}Rn and its progeny (Bq^{-1})
P_{eq}	EEQ — time-integrated exposure to EEDC (Bq s^{-1} m^{-3})
P_p	PAEE — time-integrated exposure to PAEC (J s m^{-3})
R	risk
R_{M_B}	risk of morbidity (dimen.)
R_{M_T}	risk of mortality (dimen.)
S_C	scaling coefficient for a current (mobile) population to a stationary population (dimen.)
t	time (T)
T_i	exposure time — subscript i refers to exposure for part-time cavers (50 h yr^{-1}), full-time cavers (600 h yr^{-1}), part-time cave workers (1,760 h yr^{-1}), and full-time cave workers (2,000 h yr^{-1}) (h yr^{-1})
$T_{½}$	radioactive half-life of considered radionuclide (T)
W_R	radiation weighting factor for various types of radiation (dimen.)
W_{T_i}	tissue weighting factor for differing sensitivities of various human tissues to radiations (dimen.)
ε_p	potential alpha energy per unit of activity (Bq)
λ_r	decay constant for considered radionuclide (dimen.)

ACRONYMS

DCF	Dose Conversion Factor
DNA	Deoxyribonucleic Acid
DOE	U.S. Department of Energy
EEDC	Equilibrium-Equivalent Decay-Product Concentration
EEQ	Equilibrium Equivalent Exposure
EPA	U.S. Environmental Protection Agency
HRTM	Human Respiratory Tract Model
LD50	Median Lethal Dose
LET	linear energy transfer
LNT	linear no-threshold theory
LOAEL	Lowest Observed Adverse Effect Level
MSHA	Mine Safety and Health Administration
NIOSH	National Institute of Occupational Safety and Health
NOAEL	No Observed Adverse Effect Level
NPS	National Park Service
NRC	U.S. Nuclear Regulatory Commission
OSHA	Occupational Safety and Health Administration
PAEC	Potential Alpha-Energy Concentration
PAEE	Potential Alpha-Energy Exposure

NOTES

[1] A metalloid is an element with properties intermediate between those of metals and nonmetals.

[2] Clathrate compounds are formed by trapping the ^{222}Rn in the lattice of surrounding atoms rather than forming chemical bonds.

[3] See Table 13 in the Appendix for a brief overview of radiation SI units and conversion to traditional units.

[4] The linear energy transfer (LET) of radiation is a measure of the spatial energy distribution stated in terms of the amount of energy deposited per unit length of particle track, dE/dx, with typical units of keV μm^{-1} (NRC, 1990, p. 11). It is the energy lost by charged particles in electronic collisions per unit track length where a low-LET is taken as <10 keV μm^{-1} and a high-LET is taken as >10 keV μm^{-1} (NRC, 2005, p. 375).

[5] In radiation biology, dose specifically pertains to the amount of energy ionizing radiation deposits in an organ tissue (ATSDR, 1997, p. 35).

[6] Effective dose (Sv) converts to absorbed dose (Gy) according to 1 Sv = 1 Gy × W^R.

[7] The term "plate-out" refers to the attraction of the negatively charged ion to surfaces such as a cave wall or the epithelium of the lung.

[8] *In vitro* refers to the technique of performing experiments in a test tube or in a living organism.

[9] *In vivo* refers to experiments conducted on living tissue of a whole living organism as opposed to a partial or dead organism.

[10] Phagocytized refers to the ingestion of particles or organisms by phagocytosis.

[11] The reticuloendothelial system consists of a group of cells capable of phagocytosis.

[12] Parenteral administration refers to the route of particle administration (transport) through the body.

[13]Confounding factors are associated with the finding of an association for the wrong reason. It is associated with both the risk and the disease being studied, but need not be a risk factor for the disease under study. The confounding variable can either inflate or deflate the true relative risk (Wartenberg et al., 2000).

[14]ALARA means making every reasonable effort to maintain exposures to radiation as far below the dose limits in this part as is practical consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest (U.S.NRC, 2006, 10 CER, 2006,10 CFR § 20.1003).

[15]"A mortality risk coefficient is an estimate of the risk to an average member of the U.S. population, *per unit activity inhaled or ingested for internal exposures or per unit time-integrated activity concentration in air or soil for external exposures*, of dying from cancer as a result of intake of the radionuclide or external exposure to its emitted radiations" (Eckerman et al., 1999, p. 1).

[16]"A morbidity risk coefficient is a comparable estimate [mortality estimate] of the average total risk of experiencing a radiogenic cancer, whether or not the cancer is fatal" (Eckerman et al., 1999, p. 1).

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