OPEN

Paper

A Review of Radon Exposure in Non-uranium Mines—Estimation of Potential Radon Exposure in Canadian Mines

Jing Chen[1]

Abstract—**A worldwide review of radon exposure in non-uranium mines was conducted. Based on the reported radon measurements in a total of 474 underground non-uranium mines, the average radon concentration in underground non-uranium mines was calculated to be 570 Bq m^{-3} (varied from below detection limit to above 10,000 Bq m^{-3}), and the average equilibrium factor between radon and its short-lived progeny was 0.34 (varied from 0.02 to 0.9). Using the average values from the review, annual effective radon doses to workers in Canadian non-uranium mines were estimated. For underground workers, the estimated annual effective radon dose to non-uranium miners was 3.8 mSv with the possibility of varying from 0.22 to 10 mSv depending on ventilation and other operation conditions. In Canada, the majority of mines are open-pit surface mines; only a small portion of the workforce in non-uranium mines physically work underground where radon concentration can be elevated. Averaged over the entire mining workforce, occupational exposure to radon in non-uranium mines is estimated to be 0.9 mSv. The results of this study indicate that there is potential for workers in non-uranium mines to reach or exceed Canadian thresholds for mandatory monitoring and reporting radiation doses, at least for underground operations.**
Health Phys. 124(4):244–256; 2023

INTRODUCTION

Radon (^{222}Rn) is a naturally occurring radioactive gas generated by the decay of uranium-bearing minerals in rocks and soils. Exposure to radon and its short-lived progenies in air has long been identified as the second leading cause of lung cancer after tobacco smoking (NAS/NRC 1988, 1999; WHO 2009; ICRP 1993, 2014; UNSCEAR 1982, 2000, 2020). While exposure to indoor radon is the main source of natural radiation exposure to the population, lung cancer caused by exposure to radon decay products is the most common type of radiation-induced injury among occupationally exposed workers. Underground atmospheres have increased potential for radon exposure, especially in mining of uranium and associated substances such as copper, phosphorous, calcium, arsenic, barium, vanadium, and lead. As indicated in several reports of United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1982, 1993, 2000, 2008), exposure to radon represents the most significant contribution to occupational radiation exposure in underground mining operations.

In most underground uranium mines, radon doses to miners are strictly controlled and determined by monitoring radon progeny concentrations directly in the units of working levels (WL) (1WL = 2.08 × 10^{-5} J m^{-3}) and radon progeny exposure in working level month (WLM). Unlike in uranium mines, radon exposure in non-uranium mines is normally not under regulatory control. Continuous monitoring and control of the radiation exposure levels of workers is not undertaken in conventional mines in many countries since, as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2022), exposure data for non-uranium miners are very limited. For the period 2005–2009, the UNSCEAR Global Survey of Occupational Radiation Exposure only received detailed exposure data for non-uranium mining operations from four countries out of 57 United Nations member states that expressed interest in participating in the survey.

The radon-induced lung cancer is not specific only for uranium miners, because radon is a naturally occurring radioactive gas generated by the decay of uranium-bearing minerals in all rocks and soils in varying concentrations. For example, radon and γ-ray exposures were measured in 26 non-uranium mines in Australia (Ralph et al. 2020a). The results showed that, on average, exposure to radon progeny in non-uranium mines contributed to 71% of the total annual effective dose, ranging from 43% to 93% in different mines. A more recent study by Ralph and Cattani (2022) in 13

[1]Radiation Protection Bureau, Health Canada, 775 Brookfield Road, Ottawa K1A 1C1, Canada.
For correspondence contact the author at the above address, or email at Jing.chen@hc-sc.gc.ca.
(*Manuscript accepted* 28 *September* 2022)
0017-9078/23/0

DOI: 10.1097/HP.0000000000001661

non-uranium mines in Australia also included committed effective doses from inhalation of dusts containing long-lived alpha-emitting nuclides in total annual effective doses. In this case, exposure to radon progeny in non-uranium mines contributed to 29% of the total annual effective dose, ranging from 0.7% to 90% in different mines (Ralph and Cattani 2022). Radon exposure in uranium and non-uranium mines can result in occupational health concerns.

Historically, radon concentration was high in underground mines. Underground working conditions have been improved significantly in recent decades. For example, in Canada, radon progeny concentration in underground uranium mines has been kept at a historically low level for the past two decades (1998–2018) with an average annual radon exposure of 0.23 WLM, compared to the 5-y average annual radon exposure of 1.4 WLM from 1993 to 1997 (Chen et al. 2021). In Polish metal ore mines, the mean annual radon exposure has stabilized at a historically low level since the beginning of the 1980s (Kluszczynski et al. 2002). The average radon concentration in Finnish underground mines has decreased with time, being approximately 1,800 Bq m^{-3} in the year 1972, 300 Bq m^{-3} in 1990, and 100 Bq m^{-3} in 2000 (Koja et al. 2021). Therefore, this paper aimed to provide updated information on radon exposure to non-uranium underground miners based on review of more recent publications on measurements of radon and radon progeny concentrations in active underground non-uranium mines (i.e., mines in operation with ventilation on) found in the literature in recent two decades (2000 to present).

In Canada, mining associated with the nuclear fuel cycle (i.e., uranium) falls under the regulatory authority of the Canadian Nuclear Safety Commission (CNSC) and is subject to requirements for monitoring and reporting information on radiation doses to workers. Other types of mining are regulated by the provincial and territorial authorities. For CNSC-regulated uranium mining activity, miners' dose records (including radon doses) have been reported to the National Dose Registry (NDR) since 1955. However, exposure monitoring for non-uranium mining activities using a licensed dosimetry service and reporting doses to the NDR is not required. In the most recent "Report on occupational radiation exposures in Canada 2008–2018" (Health Canada 2021), dose records were only available for workers with uranium mining activities (there were 629 underground workers in uranium mines in 2018; they were uranium mine underground miners, underground workers for maintenance, and other underground personnel). To fill the data gaps for large numbers of workers employed in various non-uranium mines, radon exposures to Canadian non-uranium mine workers were estimated with radon exposure information from literature review, assuming Canadian non-uranium mines operating under similar conditions to the averages from many other non-uranium mines around the world.

REVIEW OF RADON CONCENTRATIONS IN UNDERGROUND NON-URANIUM MINES

Radon gas contributes relatively little to the dose to the lung. The inhalation of the short-lived solid radon decay products and subsequent deposition on the walls of the airway epithelium of the bronchial tree deliver most of the radiation dose to humans. The equilibrium factor, *F*, between radon and its short-lived progeny in underground mine atmospheres can be very unstable and vary in space and time in the range of 0.1–1.0 (Chen and Harley 2020). Therefore, some radon measurements in mines were direct measurements of radon progeny concentration in working level (WL) (1 WL = 2.08×10^{-5} J m^{-3}) or potential alpha energy concentration (PAEC, in units of J m^{-3}). For the purpose of comparison with residential radon gas measurements, measurement results of radon progeny concentrations were converted to radon gas concentration in the units of Bq $\times$ m^{-3} using the equilibrium factor $F = 0.38$ determined from multiple simultaneous radon gas and radon progeny measurements performed in a total of 173 underground mines of various mining types in 18 countries (Chen and Harley 2020). Therefore, 1 J m^{-3} of radon progeny concentration was converted to 4.76×10^{8} Bq m^{-3} of radon gas concentration (1 μJ m^{-3} = 476 Bq m^{-3}). Due to the importance of *F* factor in radon dose calculation, current review also collected information of measured *F* factor whenever available in the literature.

Radon measurements in a total of 142 underground coal mines in eight countries are summarized in Table 1. Weighted by numbers of mines investigated, the arithmetic mean (AM) radon concentration in underground coal mines was 285 Bq m^{-3}; mean radon concentrations in coal mines varied from 5 to 4,183 Bq m^{-3}. Measurements in China showed that radon concentrations were lower in large-sized mines with much improved working conditions. Equilibrium factors were determined with active continuous monitors during working hours in eight coal mines and varied from 0.02 to 0.9 with the mean of 0.35.

Radon measurements in a total of 201 underground metal mines in 12 countries are summarized in Table 2. Weighted by numbers of mines investigated, the average radon concentration in underground metal mines was 558 Bq m^{-3}, and the average radon concentrations in metal mines varied from below detection limit to 10,400 Bq m^{-3}. A study in manganese ore mine in Urkut, Hungary (Kavasi et al. 2009), demonstrated that the average radon concentration in the mine (817 Bq m^{-3}) measured with monomer allyl diglycol carbonate (CR-39) over a year was about two times higher than the average radon concentration during the working shift of miners (412 Bq m^{-3}) recorded by personal dosimeters over the same time period during working hours. This difference is the result of the ventilation system that reduces radon concentration during working hours. Equilibrium factors

Table 1. Review results of radon measurements in 142 underground coal mines with mean radon gas concentrations and/or ranges as well as measured F factors in eight mines.

Country	Location/name	No. of mines investigated	Monitoring locations/points	Type of measurements	Rn in air, Bq m^{-3} AM±SD (min, max)	F-factor AM±SD (min, max)	Reference
Australia	West Australia	3	-	6 mo with CR-39 for Rn, Alpha Prism II for RnP	141 ± 76 (68, 220)	0.91 (result in 1 mine)	Ralph et al. 2020b
Brazil	Paraná State	1	18 points	AlphaGuard™	227 ± 59 (7, 771)	-	Salim and Bonotto 2019
Brazil	Underground coal mines	5	-	-	600 ± 787 (21, 1830)	0.3 (result in 1 mine)	Ayres de Silva et al. 2018
China	Underground coal mines in 6 provinces	14	85 points in 14 mines	> 90-d tests with passive Rn/Tn detectors	80 ± 106 (5, 1784)	0.34 ± 0.05 (0.14, 0.74) (result in 1 mine)	Shang et al. 2015, 2008
China	Underground coal mines in Beijing, Shanxi, Hunan, Zhejiang, Guizhou	8	718 points in 8 mines	12 mo with KF606 monitor	530 (40, 3187)	-	Chen et al. 2006
China	Underground coal mines in 12 provinces	48	943 with KF606; 218 with RAD7	long-term monitoring with KF606 and RAD7 monitors	400 (14, 4183)	-	Chen et al. 2008
	large-sized coal mines	12			47 (18, 65)		
	medium-sized coal mines	16			223 (22, 1963)		
	small-sized coal mines	16			630 (14, 3187)		
	bone coal mines	4			1244 (136, 4183)		
China	large-scale coal mine	1	10 (environ. monitoring)	CR-39 and KF606 monitor for 2-y measurement	169 (48, 318)	-	Fan et al. 2016
India	Incline coal mines of Godavarikhani	2	30 locations in a mine	3-mo tests with solid-state nuclear track detectors for 1 y	230 ± 66 (37, 414)	0.44 (0.29, 0.91)	Rao et al. 2001
Iran	Coal mines in Pabdana, Babnizoo, Karsang, Eshkeli, Tazareh, Sangrud and Karmozed	7	10–12 locations where miners had max. occupacy in each mine	Short-term measurements with PRASSI™ meter and activated charcoal method	321 ± 109 (146, 520)	-	Ghiassi-Nejad et al. 2002
Iran	Coal mines of Karsang and Karmozed	2	10–15 points in each mine	PRASSI™ meter and AlphaGuard™ in 10–15 d during mining activities	220 (40, 590)	0.1 (0.02, 0.3)	Fathabadi et al. 2006
Pakistan	Coal mines of Baluchistan	6	6 points in each mine	30-d measurements with CN-85 track detectors	192 (121, 408)	-	Qureshi et al. 2000
Pakistan	Chakwal coal mines	5	6 points in each mine	3-mo measurements with CN–85 track detectors	89 ± 28 (50, 114)	-	Mahmood and Tufail 2011
Poland	Underground galleries of coal mines	4	30 points in 4 mines	alpha spectrometer	609 (10, 3369) (232 EEC, assuming F = 0.38)	-	Skubacz and Michalik 2002
Poland	Experimental mine: Barbara	1	2 levels, 30 m and 46 m	PAEC continuous monitoring with RAD7 and AlphaGuard from 2012 to 2021	261 (0.55 μJ m^{-3}, (<0.1, 2.31), assuming F = 0.38)	-	Bonczyk et al. 2022

Poland	Hard coal mine	1	7 points in the mine	Two particle spectrometers used during day time over 2 y	148 ± 111 (0.31 ± 0.23 μJ m^{-3}, assuming F = 0.38)	-	Skubacz et al. 2016
Poland	Hard coal mine in R-15 longwall area	1	2 locations	6-mo alpha track detector measurements, RGR-40 radiometers for PAEC during working hours	82 ± 6	0.16 (0.12, 0.20)	Skubacz et al. 2019
Poland	Underground coal mines	21	3600 measurements in 2018	PAEC measurements with Alfa-31 probes according to Polish Standard PN-88/Z-70071	67 ± 57 (0.14 ± 0.12 μJ m^{-3}, assuming F = 0.38)	-	Wysocka et al. 2021
Turkey	bituminous coal mines in Zonguldak	5	14 points	Active charcoal	20 (<15, 78)	-	Emirhan and Ozben 2009
Turkey	lignite mines (Tuncbilek, Omerler and Eynez)	3	5 points in each mine where miners had max. occupacy	2-mo measurements with CR-39, 50 detectors for each mine	239 (50, 587)	-	Cile et al. 2010
Turkey	Karadon, Kozlu and Uzulmez coal mines in Zonguldak	3	42 points in 3 mines	6 wk measurements with CR-39	679 ± 242 (253, 1470)	-	Fisne et al. 2005
Turkey	Amasra coal mine in Zonguldak	1	12 points	40-d measurement with CR-39	117 (49, 223)	-	Baldik et al. 2006
Summary		142			285 (5, 4183)	0.35 (0.02, 0.91)	

Table 2. Review results of radon measurements in 207 underground metal mines with mean radon gas concentration and/or range as well as measured F factors in 28 mines.

Country	Location/name	No. of mines investigated	Monitoring locations/points	Type of measurements	Rn in air, Bq m^{-3} AM±SD (min, max)	F-factor AM±SD (min, max)	Reference
Australia	A metalliferous mine at Bamford Hill in North Queensland	1	16 locations	RADUET detectors for 70–90 d, and SARAD EQF3200 for 4 d	140 ± 55 (60, 390)	0.17	Kleinschmidt et al. 2018
Australia	West Australia	23	-	6 mo with CR-39 for Rn, Alpha Prism II for RnP	57 ± 46 (16, 172)	0.38 ± 0.26 (0.17, 0.91) (results in 8 mines)	Ralph et al. 2020b
Brazil	Tourmaline mine	1	-	-	4964 (1392, 10880)	0.2	Ayres de Silva et al. 2018
China	large-scale metal mines	2	10 (environmental monitoring)	CR-39 and KF606 monitor for 2-y measurement	1148 (115, 2459)	-	Fan et al. 2016
China	Metal mines in 10 provinces	25	147 points in 25 mines	> 90 d tests with passive Rn/Tn detectors, continue monitors	1214 ± 2358 (11, 19600)	0.33 ± 0.15 (0.10, 0.55) (results in 9 mines)	Shang et al. 2015
Germany	TUBAF mine	1	1 location 50 m from Reich Zeche shaft	24 h monitoring with RAD7	805 ± 10	-	Polaczek-Grelik et al. 2019
Ghana	Gold mine in Ashanti Region of Ghana	1	3 points in mine	60-min monitoring with AlphaGuard PQ2000 Pro	400 ± 49 (295, 474)	-	Darko et al. 2005
Ghana	Artisanal gold mines in upper east region	7	3 points in each mine	3-mo measurements with LR-115 detectors	98 ± 22 (14, 270)	-	Doyi et al. 2013
Hungary	Manganese ore mine in Urkut	1	11 locations	Solid state NRPB and Raduet, 3-mo measurements over 2 y	744 ± 37	-	Shahrokhi et al. 2017
Hungary	Manganese ore mine in Urkut	1	2 locations	Continue monitoring with EQF3020 recorded every 2 h during working hours for 9 d	375 (110, 820)	0.41 (0.21, 0.74)	Kavasi et al. 2011
Hungary	Manganese ore mine in Urkut	1	9 points in the mine	CR-39 monthly over 1 y for Rn. Pylon WLX and AlphaGUARD Pro2000 for F during working hours for 16 d	817 (575, 997)	0.57 (0.1, 0.8)	Kavasi et al. 2009
			3 teams of workers	Personal track-etched detector during working hours over 1 y	412 (205, 984)	-	
Hungary	Manganese ore mine in Urkut	1	20 locations in the mine	6 mo with RADOPOT passive detectors	924 (308, 1639)	-	Kavasi et al. 2007
Iran	Metal mines in Robat-Karim, Nakhlak and Venarge-Qom	3	8–10 locations where miners had max. occupacy in each mine	Short-term measurements with PRASSI survey meter and activated charcoal method	510 ± 104 (10, 1332)	-	Ghiassi-Nejad et al. 2002
Iran	Metal mines	9	10–15 points in each mine	PRASSI™ meter and AlphaGuard™ in 10–15 d during mining activities	796 (<2, 10400)	0.50 ± 0.19 (0.1, 0.9) (results in 7 mines)	Fathabadi et al. 2006
Kosova	Stanterg, Artana, Hajvali and Badovc mine	4	138 points in Stanterg, 89 points in Artana, 53 points in Hajvali, 66 points in Badovc mine	4 d continue monitoring with CRM-510	371 ± 20 (60, 748)	-	Hodolli et al. 2015

Kosova	Trepca mine	1	226 measurements in various points of 4 horizons of mining activities	6-mo measurements with CRM-510 and PRM-145	286 ± 146 (54, 691)	-	Bekteshi et al. 2017
Poland	Polkowice-Sieroszowice copper mine	1	5 points at salt layer 930 m below surface in 2010, one point at anhydrite layer 1014 m below surface in 2020	Continue monitoring with AlphaGuard PQ2000 in 2010, 1-h measurement cycle for 2 d with RAD7 in 2020	25 ± 18 (0.6, 101)	-	Szkliniarz et al. 2021 Kisiela et al. 2010
South Africa	Driefontein Gold Mine in Carltonville	1	Measurements were taken at levels 18, 20, and 36 of shaft #6	Short-term measurements with Lucas cell for Rn and portable spectrometer ML98B RSR for RnP	1842 ± 66	0.58 (0.4, 0.8)	Ntwaeaborwa et al. 2004
Ukraine	Active iron mines in Kryvbas	5	Short-term monitoring in 2018–2019	AlphaGuard^{TM} PQ2000	1468 (EEC 558, (1.5, 3204)) (assuming F = 0.38)	-	Molchnanov et al. 2020
USA	Metal mines	118	856 records	Area monitoring data 2000–2015 from MSHA database	440 (0.03–0.08WL, assuming F = 0.38)	-	Daniels and Schubauer-Berigan 2017
Summary		207			558 (<2, 10,400)	0.40 (0.10, 0.91)	

Table 3. Review results of radon measurements in 74 underground non-metallic mineral mines with mean radon gas concentration and/or range as well as measured F factors in 25 mines.

Country	Location/name	No. of mines investigated	Monitoring locations/points	Type of measurements	Rn in air, Bq m^{-3} AM±SD (min, max)	F-factor AM±SD (min, max)	reference
Brazil	Conventional underground mines	8	-	-	841 ± 798 (25, 2414)	0.40 (0.2, 0.7) (results in 4 mines)	Ayres de Silva et al. 2018
China	Non-metal mines in 4 provinces	4	33 points in 4 mines	> 90-d tests with passive Rn/Tn detectors, continue monitors	69 ± 52 (5, 169)	-	Shang et al. 2015
Egypt	Underground phosphate mines along the Red Sea shore	9	10–39 locations in a mine	Scintillation cell method	5772 ± 3867 (1311, 12448)	0.28 ± 0.18 (0.05, 0.57)	Bigu et al. 2000
Egypt	Abu-Tartor phosphate mine	1	20 locations along the mine tunnels	Short-term measurements with Pylon-150 for Rn and Pylon-RN190 for RnP	4187 ± 685 (1801, 5535)	0.35 ± 0.14 (0.19, 0.49)	Khater et al. 2004
Iran	Phosphate mine in Jairoud	1	10 points	PRASSI™ meter and AlphaGuard™ in 10 d during mining activities	150 (50, 390)	0.18 (0.1, 0.3)	Fathabadi et al. 2006
Romania	Salt mines in northern Romania	3	2–4 points in a mine	3-y monitoring with Pylon AB-5 with ventilation on	26 (4.7–60.2)	-	Calin et al. 2012
USA	Non-metal mines	48	557 records	Area monitoring data 2000–2015 from MSHA database	467 (0.01–0.08WL, assuming F = 0.38)	-	Daniels and Schubauer-Berigan 2017
Summary		74			1159 (5, 12448)	0.26 (0.05, 0.7)	

were determined in 28 metal mines and varied from 0.1 to 0.9 with the mean of 0.40.

Radon measurements in a total of 74 underground non-metallic mineral mines in six countries are summarized in Table 3. Weighted by numbers of mines investigated, the average radon concentration in underground non-metal mines was 1,159 Bq m^{-3}; the average radon concentrations in non-metal mines varied from 5 to 12,448 Bq m^{-3}. Equilibrium factors were determined in 25 non-metal mines and varied from 0.05 to 0.7 with the mean 0.26.

Radon measurements in other 51 underground non-uranium mines without identifying ore types in three countries are summarized in Table 4. Weighted by numbers of mines investigated, the average radon concentration in the 51 underground non-uranium mines was 593 Bq m^{-3}, and the average radon concentrations in the non-uranium mines varied from 28 to 4,153 Bq m^{-3}. Santos et al. (2014) studied six non-uranium mines (agalmatolite, coal, emerald, fluorite, scheelite, and tourmaline extraction) in Brazil. Among the five mines in operation, the lowest radon concentration of 122 Bq m^{-3} was observed in a mine with highest air velocity (1.8 m s^{-1}). The highest radon concentration of 4,153 Bq m^{-3} was found in a mine with air velocity less than 0.1 m s^{-1}; radon concentration in this mine increased to 4,964 Bq m^{-3} with the ventilation system turned off (Santos et al. 2015). In mines out of operation, the radon concentrations were all above 1,000 Bq m^{-3} (Santos et al. 2014, 2015). The yearly average radon concentrations of the Finnish study (Koja et al. 2021) were calculated without very high results in two mines with no active mining (thus poor or non-existent ventilation) in 2015 and 2019. Equilibrium factors were determined in five non-uranium mines in Brazil and varied from 0.2 to 0.7 with the mean of 0.42.

Summaries of literature review for non-uranium mines reported since the year 2000 are presented in Table 5. The review of reported radon measurements in a total of 474 underground non-uranium mines showed very wide variation in radon concentration as well as the F-factor. Radon concentrations measured in various underground non-uranium mines varied from below the detection limit to over 10,000 Bq m^{-3}. The results in Table 5 showed that, on average, radon concentration was lower in coal mines, followed by metal mines, and higher in non-metal mines. Averaging over 474 underground non-uranium mines gave an average radon concentration of 574 Bq m^{-3}. Simultaneous radon and radon progeny measurements for determination of F-factor were reported in 66 underground non-uranium mines. Like radon concentration, the F-factor also varied widely from 0.02 to 0.9. The average F-factor seemed to be lower in non-metal mines, followed by coal mines and metal mines. Averaging over reported data sets in 66 underground non-uranium mines gave an average F

Table 4. Review results of radon measurements in 51 underground non-uranium mines without specifying ore types mined with mean radon gas concentration and/or range as well as measured F factors in five mines.

Country	Location/name	No. of mines investigated	Monitoring locations/points	Type of measurements	Rn in air, Bq m^{-3} AM±SD (min, max)	F-factor AM±SD (min, max)	Reference
Australia	Underground non-uranium mines in Western Australia	7	-	Doses of mine workers reported by mining operations 2018–2019	45 (0.34 mSv, using 12 mSv/WLM, F = 0.2, assuming 2,000 h)	-	Ralph et al. 2020a
Brazil	Non-uranium underground mines in southeastern and northeastern regions	33	-	CR-39 detectors for 90–180 d	637 (28–2433)	-	Fraenkel et al. 2008
Brazil	Underground mines (agalmatolite, coal, emerald, fluorite, scheelite and tourmaline) in operation with ventilation	5	In each mine, 2–8 points were selected along their full lengths, from the entrance of fresh air to its exhaust point	3-mo Rn measurements with CR-39 detectors and 2-d RnP measurement with AlphaGuard PQ2000Pro.	1347 (122, 4153)	0.42 (0.2, 0.7)	Santos et al. 2014
Finland	Active non-uranium mines (gold, calcite, limestone, copper, zinc, ferrochrome, silver, cobalt, and nickel)	13	408 measurements during 2011–2019	Track etch detectors for a few weeks	168 ± 34 (90, 1100)	-	Koja et al. 2021
Summary		51			593 (28, 4153)	0.42 (0.2, 0.7)	

value of 0.34, similar to a previous review result of 0.38 based on studies from more than 26 countries measured in 173 underground mines, including uranium mines (Chen and Harley 2020).

ESTIMATION OF POTENTIAL RADON EXPOSURE IN CANADIAN MINES

In Canada, radon levels in non-uranium mines are generally not available because radon exposure in non-uranium mines is not under regulatory control. To fill the data gaps for large numbers of workers employed in various non-uranium mines, potential radon exposures to Canadian workers in non-uranium mines were estimated with radon exposure information from the literature review, as summarized in Table 5 for underground non-uranium mines.

Mining workforce in Canada

The mining industry has contributed greatly to Canada's economic strength—from diamonds in the Northwest Territories to coal in British Columbia, to uranium and potash in Saskatchewan, to gold in Ontario and Quebec, and to iron in Newfoundland. The mining industry comprises establishments primarily engaged in mining or preparing metallic and non-metallic minerals. It is composed of three segments: coal mining (13% of total production in 2018); metal ore mining (55%); and non-metallic mineral mining and quarrying (32%) (MAC 2022). Averaged over 5 y (2016–2020), there were 72,308 workers directly employed in mining extraction; 40,325 workers in metal mining (65% are miners); 24,634 workers in non-metal mining (69% are miners); and 7,349 workers in coal mining. Employment is mostly concentrated in Ontario (26%), Quebec (24%), British Columbia (19%), and Saskatchewan (12%), and the workforce is primarily composed of men (85%). The number of workers employed in the mining industry and the production from 2016 to 2020 are summarized in Table 6.

Like in many other countries, some mines in Canada are underground mines. Some historical underground mines have been converted to surface mines in recent decades, and many more mines are now operating as open-pit surface mines. According to Mining Association of Canada (MAC 2022), among 19 producing coal mines in 2020, only one coal mine in Nova Scotia has been active underground with 0.5 million tons (MT) of coal production in 2018 (https://miningdataonline.com/property/1713/Donkin-Mine.aspx), less than 1% of Canadian coal production. This indicates that almost all Canadian coal mines with more than 7,000 employees are working in surface mining.

According to Mining Association of Canada (MAC 2022), in 2020 there were 80 active producing metal mines (including one uranium mine) in Canada, and 46 of them (including one uranium mine) were operating underground, with nine of them operating in a combined mode of surface

Table 5. Summary of radon concentrations and *F*-factors in underground non-uranium mines reported in the literature since 2000.

Mining type	No. of mines measured for Rn	Rn in air, Bq m^{-3} mean (min, max)	No. of mines Measured F-factor	*F*-factor mean (min, max)
Coal	142	285 (20, 679)	8	0.35 (0.02, 0.9)
Metal	207	558 (25, 4964)	28	0.40 (0.1, 0.9)
Non-metallic	74	1159 (5, 12448)	25	0.26 (0.05, 0.7)
Other non-uranium	51	593 (28, 4153)	5	0.42 (0.2, 0.7)
Summary	474	574 (5, 12448)	66	0.34 (0.02, 0.9)

and underground mining, and 25 of them were surface mines. In 2020, there were 94 active producing non-metal mines in Canada; 18 of them were underground mines, two were open-pit and underground combined, and 74 were open-pit surface mines.

Even though most metal and non-metal mines are open-pit surface mines, 37% of Canadian mines operate underground, mainly metal mines in Ontario and Quebec and non-metal mines in Saskatchewan. In underground mines, not all employees are underground workers. In the mining industry, the key occupations (4-digit National Occupational Classification (NOC)) include:

- Underground production and development miners (8231);
- Supervisors, mining and quarrying (8221);
- Heavy-duty equipment mechanics (7312);
- Underground mine service and support workers (8411);
- Construction millwrights and industrial mechanics (7311);
- Transport truck drivers (7511);
- Managers in natural resources production and fishing (0811);
- Industrial electricians (7242);
- Mine labourers (8614);
- Geological and mineral technologists and technicians (2212);
- Geoscientists and oceanographers (2113);
- Mining engineers (2143); and
- Geological engineers (2144).

Among those job classes, underground production and development miners (NOC 8231) and underground mine service and support workers (NOC 8411) are underground workers. Mine labourers (NOC 8614) carrying out a variety of general labouring duties to assist in the extraction of minerals and ore may also work underground.

Averaged over 2016 and 2017 (Statistics Canada 2018), there were 7,480 underground production and development miners (NOC 8231); 5,225 underground mine service and support workers (NOC 8411); and 3,973 mine labourers (NOC 8614). Because the majority of mines in Canada are surface mines, it is estimated that only 37% (or about 1,470) of mine laborers work in an underground mining environment. Adding the three categories combined gives a total of 14,175 workers performing underground duties in Canadian mines. According to the report from National Dose Registry (Health Canada 2021), averaged over the same period (2016–2017), there were 990 underground workers and 2,411 surface workers in uranium mines.

Based on available information, the above analysis showed that of the more than 72,300 workers employed in coal, metal, and non-metal mines across Canada, about 67% of them were miners. Among the estimated 48,446 miners, 14,175 are underground mine workers and 34,271 are surface mine workers. Among the 14,175 underground mine workers, about 13,185 (93%) are in non-uranium mines excluding coal mines. Among the 34,271 surface mine workers, about 31,860 (93%) are in non-uranium mines, including 4,924 (estimated as 67% of 7,349) coal mine workers.

According to Canadian Labour Statistics (Statistics Canada 2022), on average, miners work a total of 2,139 hours annually (2,091 hours in coal mining, 2,165 hours in metal mining, and 2,161 hours in non-metal mining). All other

Table 6. Number of employments and productions in metal mines, non-metal mines and coal mines in Canada from 2016 to 2020 (MAC 2022; NRCan 2021).

		2016	2017	2018	2019	2020	Average
Metal mines	Workers	38765	39360	40795	41100	41605	40325
	Miners	25658	25068	26957	-	-	25894
	Production ($B)	23.302	25.738	27.059	28.924	28.516	26.708
Non-metal mines	Workers	22490	24280	25255	25300	25845	24634
	Miners	15854	17324	16459	-	-	16546
	Production ($B)	12.108	13.304	15.531	13.174	11.406	13.105
Coal mines	Workers	7320	7045	7535	7845	7000	7349
	Production ($B)	4.009	6.28	6.459	5.625	3.958	5.266
	Production (MT)	61.33	60.75	54.60	51.75	40.79	53.84

Table 7. Annual average number of hours worked for paid workers in mining industry (2016 to 2020) (Statistics Canada 2022).

North American Industry Classification System (NAICS)	2016	2017	2018	2019	2020	Average
Coal mining [2121]	2,113	2,144	2,088	2,066	2,043	2,091
Metal ore mining [2122]	2,164	2,190	2,169	2,263	2,041	2,165
Non-metallic mineral mining and quarrying [2123]	2,143	2,155	2,169	2,190	2,150	2,161
Support activities for mining [21311B]	2,297	2,389	2,388	2,335	2,259	2,334

support personnel for mining work 2,334 hours a year. Details are given in Table 7.

Estimation methods

Radon exposure to non-uranium mine workers is estimated in three groups: underground miners, surface miners, and other supporting personnel. For the group of underground miners, it is assumed that they are exposed to an average radon concentration of 574 Bq m^{-3} with average F factor of 0.34 for 2,139 working hours a year. For the group of surface miners, it is assumed that they are exposed to the average outdoor radon concentration of 18 Bq m^{-3} in Canada (Grasty 1994) with a mean F of 0.6 for 2,139 working hours a year. For all other support personnel, it is assumed that they are exposed to average indoor radon concentration of 34 Bq m^{-3} in Canadian indoor workplaces (Whyte et al. 2019) with an average F of 0.4 for 2,334 h y^{-1}.

The annual effective dose, E, due to radon exposure is calculated with the formula below (UNSCEAR 2020):

$$\mathrm{E(mSv)} = C_{\mathrm{Rn}} \cdot F \cdot h \cdot 9 \cdot 10^{-6}, \tag{1}$$

where C_{Rn} is radon gas concentration in Bq m^{-3}, F the equilibrium factor, h the annual working hours, and 9×10^{-6} the dose conversion factor in units of mSv (h Bq $m^{-3})^{-1}$.

Estimation results and discussion

Potential radon exposure received by Canadian workers in non-uranium mines was estimated with radon exposure information from the above literature review, assuming Canadian non-uranium mines operate in similar conditions as the averages from many other non-uranium mines around the world. The estimated annual effective doses for workers employed in Canadian non-uranium mines are given in Table 8. The estimated annual effective radon dose for underground mining workers was 3.76 mSv. Annual effective radon doses to surface mining workers and other support personnel were calculated to be much lower at 0.21 and 0.29 mSv, respectively. Weighted by number of workers in different types of jobs, the annual effective dose due to radon exposure in non-uranium mine workplaces is estimated to be 0.91 mSv.

The annual effective dose of 3.76 mSv for underground non-uranium mining workers was estimated, assuming miners exposed to the worldwide average radon concentration of 574 Bq m^{-3} in underground non-uranium mines with average F factor of 0.34 for 2,139 working hours a year. As indicated in Table 5, from a literature review of 474 underground non-uranium mines, both radon level and F-factor vary widely in underground workplaces. Consider the variation range of radon concentrations from 5 to 12,448 Bq m^{-3}, the estimated annual effective dose can vary from 0.03 to 81.5 mSv with average F-factor of 0.34 for 2,139 working hours a year. However, it would be unlikely that miners work in the lowest or highest radon spots for an entire year. Consider the variation range of F-factor from 0.02 to 0.9; mainly due to ventilation and other operation conditions, the estimated annual effective dose can vary from 0.22 to 9.95 mSv with exposure to average radon level of 574 Bq m^{-3} for 2,139 working hours a year.

Even though radon exposure in underground non-uranium mines is not available in Canada, radon exposure in underground uranium mines has been recorded in the National Dose Registry (Health Canada 2021). In the past two decades (1998–2018), the average annual radon exposure to underground uranium miners was 0.23 WLM [1 WLM = $(6.37 \times 10^5/\mathrm{F})$ h Bq m^{-3}]. An exposure of 0.23 WLM would imply an exposure to a radon concentration of 201 Bq m^{-3} for 2,139 h y^{-1} with $F = 0.34$. Using eqn (1), the average annual radon dose to Canadian underground uranium miners is 1.32 mSv, which is about one-third of the above estimated average annual effective radon dose of

Table 8. Annual effective doses, E (mSv), due to radon exposure in non-uranium mining workplaces.

Non-uranium mine workers	Number of workers	Mean Rn (Bq m^{-3})	Annual hours	*Mean* F-factor	E (mSv)
Underground mining worker	13,185	574	2139	0.34	3.76
Surface mining worker	31,860	18	2139	0.60	0.21
Support personnel for mining	23,854	34	2334	0.40	0.29
Summary	68,899				0.91

3.76 mSv to underground workers in non-uranium mines but within the likely variation range from 0.22 to 9.95 mSv. If Canadian underground non-uranium mines follow the same operational requirements as uranium mines regulated by the CNSC, the average radon concentrations could be comparable in underground mines whether uranium or non-uranium. However, without official records for non-uranium mine workers in the National Dose Registry, the radon doses received at workplaces can only be estimated based on available information from mining industries in other countries at the present time. This estimation provided a strong rationale toward mandatory monitoring and reporting radiation doses for non-uranium miners.

Outdoor radon concentration is low. Surface mine workers receive a small dose from radon exposure. Almost all Canadian coal miners are working in open-pit surface mines, and they are likely exposed to outdoor radon with an annual effective dose of 0.2 mSv.

In most indoor workplaces, radon concentration is on average significantly lower than in residential homes, mainly due to more rigorous requirements for commercial ventilation systems that result in more air changes per hour in indoor workplaces. Therefore, most support personnel in the mining industry receive radon dose on the order of 0.3 mSv.

As in uranium mines, only a small portion of the workforce in non-uranium mines physically work underground where radon concentration can be elevated. Averaged over the entire mining workforce, occupational exposure to radon in non-uranium mines is estimated to be 0.9 mSv.

CONCLUSION

Based on the review of reported radon measurements in a total of 474 underground non-uranium mines, the average radon concentration in underground non-uranium mines was calculated to be 570 Bq m^{-3}. In individual mines, radon concentrations can vary from below detection limit to above 10,000 Bq m^{-3}. The average F-factor based on measurements in 66 underground non-uranium mines was 0.34. Depending on mine operation condition, F-factor can vary from 0.02 to 0.9. With the average radon levels and F-factors in metal, non-metal, and coal mines, assessment of occupational radon exposure in non-uranium mines can be made globally. Example of such assessment was provided here for Canadian non-uranium mines where radon exposure data are missing. In Canada, the annual effective radon dose to non-uranium underground miners was estimated to be 3.76 mSv with the possibility of varying from 0.22 to 10 mSv depending on ventilation and other operation conditions. Because the majority of mines in Canada are surface mines where outdoor radon concentration is low, averaged over the entire mining workforce (underground workers, surface workers and indoor workers), occupational exposure to radon in Canadian non-uranium mining operations is estimated to be 0.9 mSv. The results of this study indicate that there is a significant potential for workers in non-uranium mining operations to receive radon doses that could reach or exceed Canadian thresholds for mandatory monitoring and reporting. It also underscores the need to further investigate radon levels in underground non-uranium mines in Canada.

REFERENCES

Ayres da Silva ALMA, de Eston SM, Iramina WS, Francisca DD. Radon in Brazilian underground mines. J Radiol Prot 38: 607–620; 2018.
Baldık R, Aytekin H, Celebi N, Ataksor B, Tasdelen M. Radon concentration measurements in the Amasra coal mine, Turkey. Radiat Protect Dosim 118:122–125; 2006.
Bekteshi S, Kabashi S, Ahmetaj S, Xhafa B, Hodolli G, Kadiri S, Alijaj F, Abdullahu B. Radon concentrations and exposure levels in the Trepça underground mine: a comparative study. J Cleaner Product 155:198–203; 2017.
Bigu J, Hussein MI, Hussein AZ. Radioactivity measurements in Egyptian phosphate mines and their significance in the occupational exposure of mine workers. J Environ Radioact 47: 229–243; 2000.
Bonczyk M, Chałupnik S, Wysocka M, Grygier A, Hildebrandt R, Tosheva Z. The determination of radon/thoron exhalation rate in an underground coal mine—preliminary results. Int J Environ Res Public Health 19:6038; 2022.
Calin MR, Zoran M, Calin MA. Radon levels assessment in some Northern Romanian salt mines. J Radioanal Nucl Chem 293: 565–572; 2012.
Chen J, Harley N. A review of radon equilibrium factors in underground mines, caves, and thermal spas. Health Phys 119: 342–350; 2020.
Chen J, Prendergast T, Prince P, Gaw A, Quayle D. The National Dose Registry—Canadian occupational exposure to ionising radiation, 1998–2018. J Radiol Protect 41:266–278; 2021.
Chen L, Pan Z, Liu S, Yang M, Xiao D, Shang B, Ma J, Wu Y, Liu F, Wang C. Primary investigation and study on ^{222}Rn and ^{220}Rn levels of underground coal mines in China. Radiat Protect 26:193–201; 2006.
Chen L, Pan Z, Liu S, Liu F. A primary assessment of occupational exposure to underground coal miners in China. Radiat Protect 28:129–137; 2008.
Çile S, Altınsoy N, Çelebi N. Radon concentrations in three underground lignite mines in Turkey. Radiat Protect Dosim 138: 78–82; 2010.
Darko EO, Tetteh GK, Akaho EHK. Occupational radiation exposure to norms in a gold mine. Radiat Protect Dosim 114: 538–545; 2005.
Daniels RD, Schubauer-Berigan MK. Radon in US workplaces: a review. Radiat Protect Dosim 176:278–286; 2017.
Doyi I, Oppon OC, Glover ET, Gbeddy G, Kokroko W. Assessment of occupational radiation exposure in underground artisanal gold mines in Tongo, Upper East Region of Ghana. J Environ Radioact 126:77–82; 2013.
Emirhan ME, Ozben CS. Assessment of radiological risk factors in the Zonguldak coal mines, Turkey. J Radiol Protect 29: 527–534; 2009.
Fan D, Zhuo W, Zhang Y. Occupational exposure to radon in different kinds of non-uranium mines. Radiat Protect Dosim 170: 311–314; 2016.
Fathabadi N, Ghiassi-Nejad M, Haddadi B, Moradi M. Miners' exposure to radon and its decay products in some Iranian

non-uranium underground mines. Radiat Protect Dosim 118: 111–116; 2006.

Fisne A, Okten G, Celebi N. Radon concentration measurements in bituminous coal mines. Radiat Protect Dosim 113: 173–177; 2005.

Fraenkel MO, De Azevedo Gouvea V, Macacini JF, Cardozo K, De Carvalho Filho CA, Lima CE. Determination of radon and progeny concentrations in Brazilian underground mines. In: 12th International Congress of the International Radiation Protection Association. Buenos Aires; 2008. Available online at ***https://inis.iaea.org/search/search.aspx?orig_q=RN:42101867***. Accessed 30 June 2022.

Grasty RL. Summer outdoor radon variations in Canada and their relation to soil moisture. Health Phys 66:185–193; 1994.

Ghiassi-Nejad M, Beitollahi MM, Fathabadi N, Nasiree P. Exposure to ^{222}Rn in ten underground mines in Iran. Radiat Protect Dosim 98:223–225; 2002.

Health Canada. Canadian guidelines for the management of naturally occurring radioactive materials (NORM). Ottawa: Health Canada; 2011.

Health Canada. Report on occupational radiation exposures in Canada 2008–2018. Ottawa: Health Canada; 2021.

Hodolli G, Bekteshi S, Kadiri S, Xhafa B, Dollani K. Radon concentration and gamma exposure in some Kosovo underground mines. Int J Radiat Res 13:369–372; 2015.

International Commission on Radiological Protection. Protection against radon-222 at home and at work. Oxford: Pergamon Press; ICRP Publication 65, Ann. ICRP 23(2); 1993.

International Commission on Radiological Protection. Radiological protection against radon exposure. Oxford: Pergamon Press; ICRP Publication 126, Ann. ICRP 43(3); 2014.

Kavasi N, Nemeth CS, Kovacs T, Tokonami S, Jobbagy V, varhegyi A, Gorjanacz Z, Vigh T, Somlai J. Radon and thoron parallel measurements in Hungary. Radiat Protect Dosim 123: 250–253; 2007.

Kávási N, Somlai J, Vigh T, Tokonami S, Ishikawa T, Sorimachi A, Kovács T. Difficulties in the dose estimate of workers originated from radon and radon progeny in a manganese mine. Radiat Meas 44:300–305; 2009.

Kávási N, Vigh T, Kovács T, Vaupotic J, Jobbágy V, Ishikawa T, Yonehara H. Dose estimation and radon action level problems due to nanosize radon progeny aerosols in underground manganese ore mine. J Environ Radioact 102:806–812; 2011.

Khater AE, Hussein MA, Hussein MI. Occupational exposure of phosphate mine workers: airborne radioactivity measurements and dose assessment. J Environ Radioact 75:47–57; 2004.

Kisiela J, Budzanowski M, Dorda J, Kozak K, Mazur J, Mietelski JW, Puchalska M, Tomankiewicz E, Zalewska A. Measurements of natural radioactivity in the salt cavern of the Polkowice–Sieroszowice copper mine. Acta Physica Polonica B 41: 1813–1819; 2010.

Kleinschmidt R, Watsona D, Janik M, Gillmore G. The presence and dosimetry of radon and thoron in a historical, underground metalliferous mine. J Sustain Mining 17:120–130; 2018.

Kluszczynski D, Jankowski J, Kacprzyk J, Kaminski Z. NORM in Polish metal-ore mines (radon exposure). International Nuclear Information System, 160–167 [online]. 2002. Available at ***https://inis.iaea.org/collection/NCLCollectionStore/_Public/34/019/34019389.pdf***. Accessed 30 June 2022.

Koja K, Laine JP, Turtiainen T, Kurttio P. Radon in Finnish underground mines 2011–2019. J Radiol Protect 41:619–627; 2021.

Mahmood A, Tufail M. Measurement of radon concentration for assessment of the radiological hazard in the Chakwal coalmines of the Salt Range, Pakistan. J Radiol Protect 31: 353–367; 2011.

Mining Association of Canada. Facts and figures 2021, the state of Canada's mining industry. Ottawa: MAC; 2022.

Molchanov O, Podrezov A, Brechko K, Soroka Y, Ishchenko L. Radon in mines of Kryvyi Rih iron ore basin in Ukraine. Radiat Protect Dosim 191:192–196; 2020.

National Academy of Science/National Research Council. Health risks of radon and other internally deposited alpha-emitters: BEIR IV. Washington, DC: The National Academies Press; 1988.

National Academy of Science/National Research Council. Health effects of exposure to radon: BEIR VI. Washington, DC: The National Academies Press; 1999.

Natural Resources Canada. Mineral industry statistics, workforce data 2016–2018 [online]. 2021. Available at ***https://mmsd.nrcan-rncan.gc.ca/MIS/MIS.aspx***. Accessed 30 June 2022.

Ntwaeaborwa OM, Kgwadi ND, Taole SH, Strydom R. Measurement of the equilibrium factor between radon and its progeny in the underground mining environment. Health Phys 86: 374–377; 2004.

Polaczek-Grelik K, Walencik-Lata A, Szkliniarz K, Kisiel J, Jedrzejczak K, Szabelski J, Mueller T, Schreiter F, Djakonow A, Lewandowski R, Orzechowski J, Tokarski P, Jalas P. Characterization of the radiation environment at TU Bergakademie in Freiberg, Saxony, Germany. Nucl Inst Meth Phys Res A 946:162652; 2019.

Qureshi AA, Kakar DM, AKram M, Khattak NU, Tufail M, Mehmood K, Jamil K, Khan HA. Radon concentrations in coal mines of Baluchistan, Pakistan. J Environ Radioactivity 48: 203–209; 2000.

Ralph MI, Chaplyn A, Cattani M. A review of radiation doses and associated parameters in Western Australian mining operations that process ores containing naturally occurring radionuclides for 2018–19. J Radiol Protect 40: 1476–1496; 2020.

Ralph MI, Hinckley S, Cattani M. Reassessment of radiation exposures of underground non-uranium mine workers in Western Australia. Radiat Protect Dosim 191:272–287; 2020.

Ralph MI, Cattani M. A review of radiation doses and associated parameters in Western Australian mining operations (2018–20). J Radiol Protect 42:012501; 2022

Rao KV, Reddy BL, Reddy PY, Ramchander RB, Reddy KR. Airborne radon and its progeny levels in the coal mines of Godavarikhani, Andhra Pradesh, India. J Radiol Protect 21: 259–268; 2001.

Salim LA, Bonotto DM. Radon exhalation rate and indoor exposure in a Brazilian coal mine. J Radioanalyt Nucl Chem 320: 587–595; 2019.

Santos TO, Rocha Z, Cruz P, Gouvea VA, Siqueira JB, Oliveira AH. Radon dose assessment in underground mines in Brazil. Radiat Protect Dosim 160:120–123; 2014.

Santos TO, Rocha Z, Vasconcelos V, Lara EG, Palmieri HEL, Cruz P, Gouvea VA, Siqueira JB, Oliveira AH. Evaluation of natural radionuclides in Brazilian underground mines. Radiat Phys Chem 116:377–380; 2015.

Shahrokhi A, Vigh T, Németh C, Csordás A, Kovács T. Radon measurements and dose estimate of workers in a manganese ore mine. Applied Radiat Isotopes 124:32–37; 2017.

Shang B, Cui HX, Wu YY, Zhang QZ, Su X. A preliminary investigation of ^{222}Rn and ^{220}Rn levels in non-uranium mines in China. Chin J Radiol Med Protect 28:559–565; 2008.

Shang B, Cui HX, Wu YY, Zhang QZ, Su X. ^{222}Rn and ^{220}Rn concentrations and miner doses in non-uranium mines in China. In: Naturally occurring radioactive material (NORM VII). Vienna: IAEA; 2015: 295–319.

Skubacz K, Michalik B. Unattached fraction of radon progeny in Polish coal mines. In: International Nuclear Information System.

2002: 278–287. Available at ***https://inis.iaea.org/collection/NCLCollectionStore/_Public/33/016/33016283.pdf***. Accessed 30 June 2022.

Skubacz K, Wojtecki L, Urban P. The influence of particle size distribution on dose conversion factors for radon progeny in the underground excavations of hard coal mine. J Environ Radioact 162–163:68–79; 2016.

Skubacz K, Wysocka M, Michalik B, Dziurzynski W, Krach A, Krawczyk J, Palka T. Modelling of radon hazards in underground mine workings. Sci Total Environ 695:133853; 2019.

Statistics Canada. Table 14-10-0001-01. Average full-time hourly wage paid and payroll employment by type of work, economic region and occupation [online]. 2018. Available at ***https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1410000101***. Accessed 30 June 2022.

Statistics Canada. North American Industry Classification System (NAICS) Canada 2017 Version 3.0 (NAICS) [online]. 2021. Available at ***https://www23.statcan.gc.ca/imdb/p3VD.pl?Function=getVD&TVD=1181553***. Accessed 30 June 2022.

Statistics Canada. Table 36-10-0489-01: Labour statistics consistent with the System of National Accounts (SNA), by job category and industry [online]. 2022. Available at ***https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610048901***. Accessed 30 June 2022.

Szkliniarz K, Walencik-Łata A, Kisiel J, Polaczek-Grelik K, Jedrzejczak K, Kasztelan M, Szabelski J, Orzechowski J, Tokarski P, Marszał W, Przybylak M, Fuławka K, Gola S. Characteristics of natural background radiation in the Polkowice-Sieroszowice Mine, Poland. Energies 14:4261; 2021.

United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 1982 Report. New York: United Nations; Publication E.82.IX.8; 1982.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, 1993, Report to the General Assembly, with scientific annexes. New York: United Nations; Publication E.94.IX.2; 1993.

United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2000 Report, Annex B—Exposures from natural radiation sources. New York: United Nations; 2000

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. Volume I: Sources: Report to the General Assembly, Scientific Annexes A and B. UNSCEAR 2008 Report. United Nations Scientific Committee on the Effects of Atomic Radiation. New York: United Nations; Publication E.10.XI.3; 2010

United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2019 Report, Annex B—Lung cancer from exposure to radon. New York: United Nations; 2020.

United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2020/2021 Report, Annex D—Evaluation of Occupational Exposure to Ionizing Radiation. New York: United Nations; 2022.

World Health Organization. WHO handbook on indoor radon. Geneva: WHO; 2009.

Whyte J, Falcomer R, Chen J. A comparative study of radon levels in federal buildings and residential homes in Canada. Health Phys 117:242–247; 2019.

Wysocka M, Skubacz K, Michalik B, Chalupnik S, Skowronek J, Bonczyk M, Chmielewska I, Samolej K. The system of monitoring and controlling natural radiation hazards in Polish coal mines. Int J Mining Mineral Engineer 12:229–249; 2021.

■■