A Review of Radon Equilibrium Factors in Underground Mines, Caves, and Thermal Spas

Jing Chen[1] and Naomi H. Harley[2]

Abstract—**Radon equilibrium factor F_{eq} is an important factor in radon progeny dose assessment. A review of published measurements of F_{eq} shows a range of values from 0.1 to 1.0 reported in studies from more than 26 countries measured in 173 underground mines, and 136 show caves, tourist mines, and thermal spas. The average values of F_{eq} are 0.38 in underground mines and 0.39 for show caves, tourist mines, and thermal spas. The wide range of F_{eq} in those special workplaces suggests that location-, environment-, and operation-specific values are more appropriate than a recommended average value in the calculation of lung bronchial dose. This is especially important in mines or other typically high radon exposure locations because F_{eq} can be used for recording an individual's occupational radon exposure or dose.**

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INTRODUCTION

RADON IS a naturally occurring radioactive gas generated by the decay of uranium-bearing minerals in rocks and soils. Radon decays further to its progenies or decay products. Radon and its short-lived progenies in the atmosphere are the most important contributors to human exposure from natural sources of radiation and have been identified as the second leading cause of lung cancer after tobacco smoking (NAS/NRC 1999; WHO 2009; ICRP 2010, 2014).

Radon (^{222}Rn) and its progenies are ever-present in the atmosphere in unattached form or attached to the local aerosol particles. Radon-222 (^{222}Rn) gas contributes relatively little to the dose to the lung. It is the inhalation of the short-lived solid radon decay products and subsequent deposition on the walls of the airway epithelium of the bronchial tree that delivers most of the radiation dose to human lungs (Harley 2018). In this paper, radon dose means radiation dose from inhalation of radon progeny.

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) (1 WL = 2.08×10^{-5} J m^{-3}). However, in many other underground workplaces, such as non-uranium mines and show caves, radon exposure is normally not under regulatory control; however, radiation protection policies may be established to monitor and manage radon exposure. In these workplaces, radon exposure constraints are given in terms of reference levels, guidelines, or recommendations based on radon gas concentration in the air. For the purpose of comparison with dose constraints/limits or other radiation exposure scenarios, it is necessary to convert or link radon gas concentration to bronchial dose. This requires the use of a bronchial dose model (Harley 2018). Dose models do not use measured radon gas concentration as input because the same radon gas concentrations can have different decay product concentrations under different environmental conditions. Instead, the radon equilibrium equivalent concentration, *EEC*, which has the same potential alpha energy concentration as the original mixture, is the input parameter to a dose model. The equilibrium factor F_{eq} is defined as the ratio of *EEC* to C_{Rn}, the radon gas concentration; i.e., $F_{eq} = EEC/C_{Rn}$. Rearranging the terms, the measured F_{eq} multiplied by the measured radon gas concentration estimates the *EEC*. Therefore, F_{eq} is an important factor in radon dose calculations.

Radon doses in many workplaces are often estimated from radon gas concentrations. Equilibrium (or disequilibrium) between radon gas and its decay products is frequently accounted for by using assumed or widely accepted F_{eq} values (for example, Dumitru et al. 2015; Fraenkel et al. 2008; Liu et al. 2017; Martin Sanchez et al. 2015; Moreno et al. 2018; Panigrahi et al. 2018), except in some workplaces where potential alpha energy concentrations or concentrations of individual radon progeny are measured directly (for example, Busigin et al. 1983; CNSC 2003; Eheman et al. 1991; El-Hady et al. 2001; Skowronek et al.

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[1] Radiation Protection Bureau, Health Canada, 775 Brookfield Road, Ottawa K1A 1C1, Canada; [2] New York University School of Medicine, 1 Marine View Plaza, Hoboken, NJ.

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For correspondence contact: Jing Chen, Radiation Protection Bureau Ottawa, Ontario Canada, or email at **jing.chen2@canada.ca**.

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1999; Skubacz et al. 2016; Yarborough and Keith 1977). The scientific literature contains many publications reporting radon gas concentrations in various working environments including underground mines, caves, and thermal spas. Direct and simultaneous measurements of radon gas and the concentrations of all short-lived decay products of ^{222}Rn are, however, limited.

Because of the importance of the factor, F_{eq}, for bronchial dose assessment, a review of measured F_{eq} in underground workplaces is conducted here. The results of a similar review, but for F_{eq} for above-ground indoor workplaces, were reported in a previous publication (Chen and Harley 2018). Workplaces considered in the current review include underground mines, tourist mines, show caves, and thermal spas.

MEASUREMENTS OF F_{eq} IN UNDERGROUND MINES

Results were collected from multiple simultaneous radon gas and radon progeny measurements performed in a total of 173 underground mines of various mining types in 18 countries. Mean radon gas concentrations and associated average F_{eq} are summarized in Table 1. All studies listed in Table 1 performed radon gas and progeny measurements in multiple locations in each mine. While the average radon gas concentration in a mine varied from 29 to 24,260 Bq m^{-3}, the average F_{eq} varied from 0.08 to 0.72. Weighted by the number of mines investigated in each study, the weighted average F_{eq} is 0.38.

The basics of equilibrium factor and various environmental factors affecting F_{eq} that were discussed in a previous publication in various indoor environments (Chen and Harley 2018) are applicable for workplaces. In addition to those common characteristics, radon gas concentrations in underground mines vary considerably depending on the type of mining and mining methods, level of radon source control used, and the presence of radon-bearing mine water. The mining environment is generally more dusty than typical workplaces, so the F_{eq} will depend heavily on the air exchange rate during mining operations, aerosol particle concentration, particle size distribution, and the unattached fraction of radon decay products in a mining area. All of those factors can differ significantly from one mine to the other. Each mine has its unique structure, mining environment, and operation.

There is an inverse correlation between the F_{eq} and unattached fraction (Porstendörfer 1996, 2001; Stranden and Berteig 1982; Stranden and Strand 1986). A positive correlation was observed between the F_{eq} and aerosol-particle concentration in the air (Butterweck et al. 1992; Cavallo et al. 1999; Huttori and Ishida 1994; Jasaitis and Girgzdys 2013; Paul et al. 2000; Porstendörfer 1978, 1996, 2001). Ventilation rate is usually the most important modifying factor for the value of F_{eq}, and an inverse relationship between the F_{eq} and air exchange rate has been observed (Bigu et al. 2000; Khater et al. 2004; Swedjemark 1983; Wicke and Porstendörfer 1981). Therefore, in a mine, F_{eq} may vary spatially and temporally, resulting in significantly different F_{eq} at different work locations. For example, the mean F_{eq} in the Olympic Dam mine in Australia was 0.20 but varied from 0.03 to 0.86 (Solomon et al. 2018), and the measured F_{eq} differed within Driefontein Gold Mine in South Africa at different levels of stopes (Ntwaeaborwa et al. 2004). Lower values of F_{eq} are always seen when measurements are near the ore or ore processing where highest ventilation rates exist. The lower values of F_{eq} in the study of Solomon et al. (2018) were at the crusher and ore pass where mined ore is transported from the stope and dumped into ore passes that feed the crushing system.

Stranden and Berteig (1982) reported a summary distribution of F_{eq} measured in a total of 210 different Norwegian mines (not necessarily underground mines), as shown in Fig. 1. The mean value of F_{eq} was 0.46 with minimum of 0.08 and maximum of 0.93. The distribution of F_{eq} followed roughly a log-normal distribution (Stranden and Berteig 1982; Tokonami et al. 1996). This indicates that using a mean value of F_{eq} for dose assessments in individual cases may lead to large errors.

Results in Table 1 showed that F_{eq} is in the range 0.1–0.7 for most mining situations. For radon dose assessments in individual mines, radon gas measurements with assumption of a universal F_{eq} would be very uncertain.

MEASUREMENTS OF F_{eq} IN SHOW CAVES, TOURIST MINES AND THERMAL SPAS

Besides active underground mines, two other workplace situations where managing occupational radon exposure could be required are show caves, including tourist mines, and radon spas. There are a number of publications reporting radon gas concentrations in these special environments. However, radon progeny measurements are again limited. Simultaneous radon gas and radon progeny measurements were found in a total of 136 underground show caves, tourist mines, and thermal spas in 17 countries. Results of mean radon gas concentrations and associated average F_{eq} are summarised in Table 2. While radon gas concentration varied from 5 to 495,800 Bq m^{-3}, the mean value of F_{eq} varied from 0.10 to 0.85. Weighted by number of those special workplaces studied, the weighted average F_{eq} is 0.39.

Unlike active underground mines, the air in show caves and tourist mines is generally much cleaner with much lower dust concentration. The air flow can be quite specific to each underground area and is normally much lower than in mining operations. As in every enclosed space, air flow

Table 1. Review results of F_{eq} studies in underground mines with mean radon gas concentration and/or range whenever available.

Country	Location	Rn, Bq m^{-3}	F$_{eq}$	Reference
Australia	Olympic Dam mine	(8, 2640)	0.20 ± 0.09 (0.03, 0.86)	Warneke and Sonter 1989; Solomon et al. 2018
Australia	A metalliferous mine at Bamford Hill	130 ± 70	0.167	Kleinschmidt et al. 2018
Brazil	8 mines (agalmatolite, coal, emerald, fluorite, scheelite, tourmaline and zinc)	1420 ± 1779 (113, 4964)	0.39 ± 0.20 (0.2, 0.7)	Santos et al. 2015
Brazil	Coal mine	6000 (5100, 7200)	0.36 (0.28, 0.46)	Veiga et al. 2004
Canada	A working diesel-powered uranium mine in northern Saskatchewan	3545 (3310, 3916)	0.078 (0.068, 0.093)	Cavallo et al. 1999
China	24 metal mines in 10 provinces	1038 ± 1760 (11, 19600)	0.33 ± 0.15	Shang et al. 2008
China	14 coal mines in 6 provinces	80 ± 106 (5, 1784)	0.34 ± 0.05	Shang et al. 2008
China	2 non-metal mines in 2 provinces	29 (5, 73)	0.33	Shang et al. 2008
China	2 phosphate mines in 2 provinces	101 (60, 169)	0.40	Shang et al. 2008
China	1 mine of rare earth ore	86 ± 69 (20, 181)	0.41	Shang et al. 2008
China	1 coal mine 37km from Beijing	760 ± 38 (319, 1083)	0.34 ± 0.5 (0.14, 0.74)	Chen et al. 1998
China	9 metal mines in 4 provinces	(37, 4980)	0.33 ± 0.15 (0.10, 0.55)	Shang et al. 2013
China	30 uranium mines	(50, 1500)	0.35	Chen et al. 2005
Egypt	9 phosphate mines	5772 (1311, 12448)	0.28 (0.05, 0.57)	Bigu et al. 2000
Egypt	Abu-Tartor phosphate mine	4187 (1801, 5535)	0.34 (0.19, 0.48)	Khater et al. 2004
Finland	23 underground mines (1972 - 1992)	110 (50% < 400, 20% > 2000)	0.64	Annanmaki et al. 2005
France	10 uranium mines	1737 (829, 3571)	0.27 (0.19, 0.33)	Rannou and Zettwoog 1991
Germany	Slate mine in Fredeburg, Barite mine in Dreslar	555 (180, 770)	0.43 (0.24, 0.58)	Butterweck et al. 1992
Hungary	a manganese ore mine in Urkut	744 ± 37	0.38 (0.2, 0.55)	Shahrokhi et al. 2017
Hungary	a manganese ore mine in Urkut	570 (133, 1495)	0.57 (0.1, 0.8)	Kavasi et al. 2009, 2011
India	Jaduguda uranium mine	963 (360, 1964)	0.5	Panigrahi et al. 2015
Iran	12 non-uranium mines	775 ± 1203 (5, 3500)	0.38 ± 0.25 (0.1, 0.8)	Fathabadi et al. 2006
Norway	an iron ore mine		0.72	Stranden and Berteig 1982
Poland	zinc-lead mine and copper mine	1480	0.26 (0.12, 0.56)	Domanski et al. 1979
South Africa	shaft #6 of Driefontein Gold Mine in Carltonville		0.58 (at level 18-stope: 0.75, at level 20-stope: 0.50, at level 36-stope: 0.50)	Ntwaeaborwa et al. 2004
Spain	the uranium mine in Saelices el Chico	627 ± 1444 (16, 4662)	0.51 ± 0.07 (0.4, 0.6)	Quindos Poncela et al. 2004
Syria	2 phosphate mines near Palmyra	592 ± 276 (230, 1149)	0.24 ± 0.12 (0.08, 0.45)	Othman et al. 1992
UK	5 coal mines	300 (27, 1244)	0.25 (0.06, 0.54)	Page and Smith 1992
US	a few uranium mines in New Mexico and Colorado	250 (27, 1278)	0.37 (0.04, 0.87)	Raghavayya et al. 1974
US	53 measurements in 6 uranium mines	24260 (3108, 85100)	0.24 ± 0.11 (0.08, 0.65)	Breslin et al. 1969

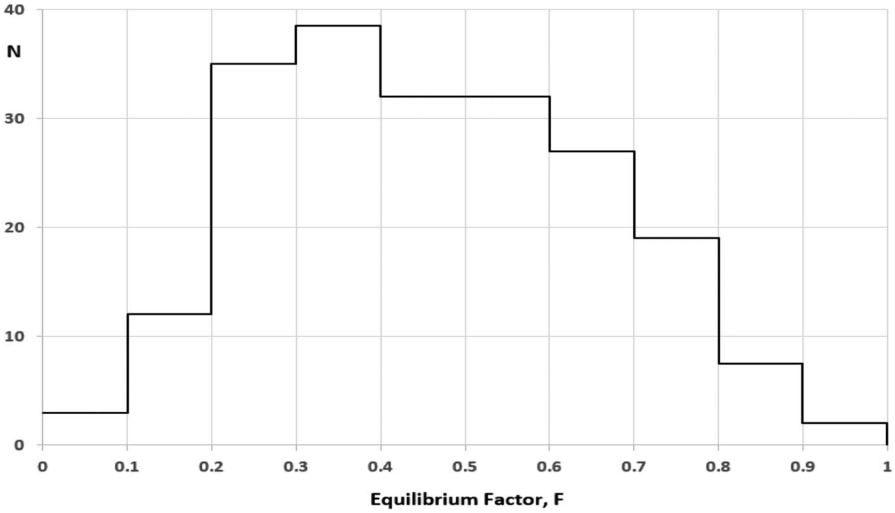

Fig. 1. Distribution of 210 measurements of the equilibrium factor in different Norwegian mines (Stranden and Berteig 1982).

significantly impacts the radon concentration and F_{eq} values in individual locations. Amano et al. (1985) measured F_{eq} in a Seismological Observatory cave, which was not ventilated. Without air flow, the observed F_{eq} was almost 1.

Table 2 also presents data from 16 spas in six countries. Thermal therapy spas are also known to have high concentrations of radon and progeny. As shown in Table 2, radon concentrations in rooms at radon spas can reach as high as 496 kBq m^{-3} (Chruscielewski 1983). These high concentrations are due to radon outgassing from the therapeutic water as well as, in some cases, a lack of windows or ventilation system.

In some parts of a thermal spa, room temperature and relative humidity are higher than the normal indoor environment. Under high humidity conditions, the F_{eq} shows a tendency to lower values, possibly due to washout. Under high humidity conditions, settling water droplets wash particles from the air, reducing the concentration of radon progeny in the air and resulting in lower F_{eq} value (Labidi et al. 2012; Vogiannis et al. 2004).

As shown in Table 2, the average F_{eq} for spas varied from 0.1 to 0.45 with an overall average of 0.30. This is somewhat lower than the overall average F_{eq} for show caves and tourist mines, which is 0.40 for 120 show caves and tourist mines.

MEASUREMENT TECHNIQUES

The measurement of F_{eq} in mines or other underground workplaces poses difficulties because of the need for rapid measurements, many times in awkward spaces with a lack of suitable electrical and other facilities. Both decay products and radon must be measured in order to determine a measured value of F_{eq}. Some epidemiological studies in uranium mines had only radon gas measurements for exposure and compliance data. In some historic studies, radon progeny exposures in working level month (*WLM*) were assumed or based on scant F_{eq} measurements. There are only a few techniques for measurement of the ^{218}Po, ^{214}Bi and ^{214}Po for the calculation of radon *EEC* concentration. Most rely on alpha counting a short duration filtered air sample or a solid-state nuclear track detector using absorbers to separate the different alpha particle energies (Page and Smith, 1992). Radon gas is typically measured by grab sampling the mine atmosphere and later sample transfer to a scintillation cell or to an ionization chamber. Radon gas is also measured using flow-through scintillation cells, pulse ionization chambers, and electrostatic-based solid state detector systems. Occasionally the two-filter method is used (Thomas and LeClare, 1970); i.e., alpha counting the second filter in a two-filter sampling tube for decay products. The decay products are freshly formed from radon in the sample tube. Recently developed instrumentation can measure the progeny concentration directly using alpha spectrometry. The ARPANSA study (Solomon et al., 2018) reported radon progeny measurements that used continuous in-situ alpha counting of radon progeny deposited on a filter.

Both recent and historic measurements of decay product concentrations in mines use the Tsivoglou method (Tsivoglou et al. 1953) or a modified Tsivoglou method (Scott 1981). This method samples filtered air for short periods of time, 5 to 30 min, followed by sequentially alpha counting the filter using an alpha scintillation counter for three count intervals. The counts are inputs to the deconvolution equations to determine the air concentration of the ^{218}Po, ^{214}Pb, and ^{214}Po. A few publications report the use of an alpha spectrometer to count the filtered air sample and obtain a value of *EEC* directly. Historically, samples were collected with fibrous filter material. After 1960, membrane filters were used that mainly solved the problem of alpha absorption

Table 2. Review results of F_{eq} studies in underground show caves, tourist mines, and thermal spas with mean radon gas concentration and/or range whenever available.

Country	Location	Rn, Bq m^{-3}	F	Reference
Australia	14 show caves in six locations	(67, 4808)	0.39 ± 0.13 (0.19, 0.75)	Solomon et al. 2005
Australia	a tourist cave	(2000, 10000)	0.45 (0.3, 0.8)	Zahorowski et al. 1998
Australia	6 tourist caves	672 (420, 1370)	0.41 (0.19, 0.52)	Solomon et al. 1992
Austria	6 tourist mines and 3 tourist caves	Caves: 960 Salt mines: 1300 Iron-ore mines: 3000 Silver mines: 4200 Copper mine: 4900	Caves and mines: 0.2 except in winter in Salt mines: 0.7 Iron-ore mines: 0.4 Copper mine: 0.54	Gruber et al. 2014
China	1 hot spring	7098 ± 4974 (580, 12460)	0.22	Shang et al. 2008
China	2 hot springs	(126, 190)	0.45	Liu and Pan 2013
China	39 limestone caves	1200 (20, 8660)	0.41	Liu and Pan 2013
Czechoslovakia	Bozkov dolomite cave		0.68	Rovenska et al. 2008
Czechoslovakia	12 tourist caves		0.26 (0.01, 0.53)	Thinova and Burian 2008
Egypt	Sannur cave	836 ± 150	0.687	Amin and Eissa, 2008
Greece	Polichnitos hot springs	(50, 3500)	0.22	Vogiannis et al. 2004
Greece	2 thermal therapy spas in Loutraki	91 ± 54 (0, 3160)	0.20 ± 0.14 (0.0, 0.28)	Nikolopoulos et al. 2010
Germany	a tourist cave	3600 (2100, 4800)	0.36 (0.29, 0.47)	Butterweck et al. 1992
Hungary	a therapeutic radon spa in Eger	98 (38, 215)	0.1 (0.03, 0.32)	Kavasi et al. 2019
Hungary	a therapeutic cave in Tapolca	4600 ± 120 (500, 12400)	0.58 ± 0.12	Kavasi et al. 2002, 2003
Hungary	3 tourist caves and 1 hospital cave	(130, 6710)	0.51 (0.48, 0.53)	Szebin 1996
Hungary	1 show cave in Tapolca	7900 (680, 15700)	0.5	Somlai et al. 2009
Ireland	3 Irish show caves	5010 (488, 11285)	0.32 (0.12, 0.71)	Duffy et al. 1996
Japan	Seismological Observatory cave (not ventilated)	(100, 900)	0.85 (0.60, 1.0)	Amano et al. 1985
Japan	3 caves in Yamaguchi		0.64 (0.52, 0.71)	Cigna 2005
Morocco	The Aouli ancient lead mine	347 (200, 525)	0.21 (0.20, 0.21)	Oufni and Amrane 2015
Morocco	2 natural caves	402 (160, 552)	0.615 (0.57, 0.63)	Misdaq et al. 2008
Morocco	2 natural caves and 2 tourist mines	494 (199, 802)	0.21 (0.20, 0.23)	Misdaq et al. 2011
Poland	3 radon spas	(5, 495800)	0.25 (0.24, 0.26)	Chruscielewski 1983
Poland	Tourist cave in Kowary Adit	(1054, 1081)	0.7 (0.6, 0.8)	Woloszczuk and Skubacz 2018
Slovenia	8 major underground wineries	280 (55, 998)	0.49 (0.25, 0.63)	Vaupotic et al. 2008
Spain	4 tourist caves	1240 ± 1363 (332, 3250)	0.50 ± 0.08 (0.4, 0.6)	Quindos Poncela et al. 2004
Tunisia	4 thermal spas	216 ± 220 (19, 870)	0.37 ± 0.13 (0.2, 0.5)	Labidi et al. 2012
US	Carlsbad Caverns	1821 ± 55	0.428 ± 0.39 (0.355, 0.481)	Cheng et al. 1997
US	Howe Caverns	634 (48, 1184)	0.67 (0.37, 0.83)	Seymore et al. 1980
Yugoslavia	natural tourist cave in Postojna	3600 (2100, 4800)	0.36 (0.29, 0.47)	Butterweck et al. 1992

attention by the sample mass. Both historic and recent measurements use the Tsivoglou method; for example, Fusamura et al. (1964) used the Tsivoglou et al. (1953) technique to measure the *EEC* in a Japanese uranium mine for dosimetric calculations. Also, the Tsivoglou et al. (1953) technique was used lately in the Australian mine study for detailed *EEC* assessments (Solomon et al. 2018).

The accuracy of all progeny measurements relies on the detector's alpha counting efficiency, a function of the mass loading of the filter, the accuracy of the sampling flow rate, the uncertainty over time, and the accuracy of any calibration sources used. Many historic measurements of the working level (*WL*) in uranium mines were also made with the Kusnetz method (Kusnetz 1956). This method used only one alpha count of a 5-min filtered air sample followed by gross alpha sample counting usually 40 min after sampling. This method measured the *WL* directly using only a single count and yields *EEC* information if radon gas measurements were also made.

Domanski developed a calculation technique based on measurement of only the ratio of ^{218}Po/^{222}Rn or ^{214}Po/^{222}Rn to estimate the F_{eq} (Domanski 1979). For example. a ratio of ^{218}Po/^{222}Rn = 0.7 would yield a F_{eq} of 0.4. Domanski used HASL-220 data to develop the technique, but it may never have been used in mines. After 1983, a personal dosimeter was used in French uranium mines for measurement of radon and thoron. The personal detector consisted of a small pump, LR115 alpha track detection film, and a system of absorbers to separate the alpha particle energies for ^{218}Po, ^{214}Po, and ^{212}Po (Rannou and Zettwoog 1991). The data for the 10 French uranium mines in Table 1 used this method.

Jonsson et al. (2010) updated lung cancer risk estimates for the Malmberget iron ore mine in Sweden based on radon measurements. Some measurements in this mine determined a calculated F_{eq} of 0.7 and measurements in two different Swedish iron ore mines had estimates of F_{eq} from 0.52 to 0.81. When radon gas measurements are made, WLM exposure in underground workplaces requires best estimates of F_{eq} for compliance with dose limits. Published measurements of F_{eq} should show all the details of the measurements for evaluation of the data. Some publications do not give the method used to measure EEC, the number of measurements made, or the locations sampled within the mine.

DISCUSSION AND CONCLUSION

It is well known that the alpha particle irradiation of the basal and secretory cells in the bronchial airways is responsible for radon-induced lung cancer seen in workers and the public. The dosimetric modeling approach for the evaluation of dose from exposure to radon and its progeny must thus take account of the actual activity concentrations of various alpha-emitting radionuclides in the air that is inhaled. In most cases, the individual activities are not directly measured. The bronchial dose is indirectly determined using assumptions made on concentration ratios; i.e., equilibrium factors and bronchial dose models. Therefore, when radon gas concentration is measured, environmental factors that influence the values of F_{eq} are of great significance for both radon progeny exposure and lung dose assessments.

The data summarized in this review demonstrate clearly that the value of F_{eq} varies widely. Environmental factors, operational conditions, and human activities and habits can affect parameters such as ventilation rate, aerosol particle plateout, and aerosol particle concentration and humidity, all of which will impact F_{eq}. Measured F_{eq} values vary widely from as low as 0.1 to as high as 1.0, or full equilibrium. For underground mines, the average of F_{eq} measurements reported here is 0.38, and for show caves, tourist mines and thermal spas, it is 0.45 +/- 0.18. These average values are consistent with the typical F_{eq} value of 0.4 adopted by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR); however, the reported measurements indicate that these workplaces represent very diverse environments.

For ^{222}Rn dosimetry, UNSCEAR recommended a typical value of $F_{eq} = 0.4$ for calculating indoor exposure. In the literature, this typical F_{eq} has been very widely used in radon dose assessment for many different workplaces, including unregulated underground mines, show caves, tourist mines and thermal spas. The International Commission on Radiological Protection (ICRP) recently issued radon dose conversion coefficients for radon inhalation in indoor workplaces, mines and tourist caves (ICRP 2017) where F_{eq} is included in the dose conversion coefficients and is fixed as 0.4 for indoor workplaces and tourist caves and 0.2 for mines. It should be mentioned that these recommended F_{eq} values are used if local environment- and operation-specific F_{eq} is unknown or not well known with the understanding that the variability in these values can be more than ±50%. If more accurate ^{222}Rn dosimetry is required to assess either ^{222}Rn bronchial dose or ^{222}Rn risk, local environment- and operation-specific F_{eq} values are the preferred parameters to use. For the reason mentioned above, radon dose conversion coefficients should be given only for radon progeny concentration (i.e., equilibrium equivalent concentration) and should not include fixed value of F_{eq}. This will allow the use of local environment- and/or operation-specific F_{eq} for more accurate radon dose estimation.

Because radon progeny exposure contributes to the largest radiation burden for most workers, knowledge of workplace radon F_{eq} is important if radon exposure is assessed. Given the ubiquity of radon, adventitious exposures to elevated radon levels are common in many underground workplaces and should be considered in occupational health and safety programs. This includes characterizing concentrations of radon and progeny as well as determining the appropriate equilibrium factors to use when assessing exposure in different work environments. Particularly in poorly ventilated or dusty environments, whether underground or above-ground, F_{eq} values are known to be significantly higher than 0.4, so exposure management strategies based entirely on radon gas concentration may not be sufficiently protective. Consideration of F_{eq} in certain work environments, such as those identified in this paper, will help ensure that workers are effectively protected.

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