Radiation doses from radon

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As part of a set of documents about detecting and confirming the presence of radon and its decay daughters, we here briefly consider the radiation *dose*. This is important because radon is a ubiquitous gas outdoors and indoors, (i) is the largest radiation dose most people receive per year, and (ii) provides a benchmark against which to compare other natural and man-made radiation doses.

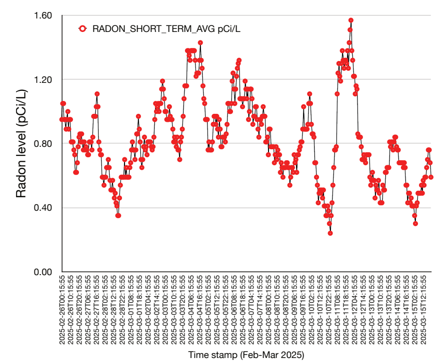

Figure 1: Typical radon levels on ground floor of a house mitigated for radon.

Radon

The EPA nominal value for outdoor radon radioactivity is 0.4 pCi/L; in Europe it is taken as 10 Bq/m^3 (0.27 pCi/L). Radon is probably the best-studied of all radiation sources since it is universal and indoor radon is almost always the largest single radiation exposure to humans; the International Committee on Radiological Protection (ICRP) has multiple publications discussing radon doses.

In the context of radon protection, limits in pCi/L (or Bq/m^3) are generally used. If required, radiation *doses* may be computed using International Committee on Radiological Protection 'dose coefficients' which relate radioactivity to "effective radiation dose" in Sieverts (Sv). The dose coefficient for an inhaled radionuclide is the effective dose per decay if the exposure time is in seconds

The 'effective dose' includes the full biochemistry and biokinetics of the nuclide as it is dispersed around the body and is the best single measure of total health consequences, including cancer.

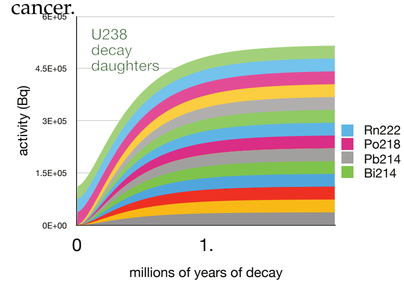

Figure 2: Radon and three main progeny are part of the ^{238}U decay chain. In 'equilibrium' the radioactivity of each is identical (equal 'layer' thicknesses.)

As a gas, radon (^{222}Rn) requires more careful treatment than many solid radionuclides. Only 2-5% of the radiation dose comes from radon itself [1], the rest from decay progeny ('daughters'): "Progeny...regardless of...location, ...are never totally in radioactive equilibrium with radon." Since the half-life of ^{222}Rn is much longer than for the others, all four can be in approximate radioactive 'equilibrium' provided they are not separated from one another via ventilation or the 'plating out' of charged daughters on tiny dust particles, which often end up on surfaces.

This is universally described by an "equilibrium factor" f_{eq} (the weighted sum of the main progeny concentrations divided by the radon concentration [1]), usually taken to be 0.4 indoors (range: 0.1-0.8) [2]. Multiplied by this factor, the radon concentration is referred to as the 'equilibrium equivalent concentration' (EEC) which could then be used in the dose calculation. *Outdoor* radon is described by a somewhat larger equilibrium factor (0.6) [2], which we will use below.

nuclide	half life	emits	dose coef
^{222}Rn	3.82 d	α	4.27×10^{-10}
^{218}Po	3.10 m	α	2.00×10^{-9}
^{214}Pb	26.80 m	α	1.20×10^{-8}
^{214}Bi	19.90 m	β	9.70×10^{-9}

Table 1: Half-lives and dose coefficients (Sv/Bq) for radon and three principal progeny. The very small dose coefficient of radon means that it barely contributes to dose.

There are a couple of approaches that would give reasonable radon dose estimates given the (i) radon concentration and (ii) assumed concentrations of the three main radon daughters, the breathing rate, and the duration of exposure. Given an assumed breathing rate BR in liters per minute (L/min) we can write for the total dose D per year in μSv as

$$\begin{aligned} D &\simeq 37{,}000\ \text{BR} \times [60 \times 24 \times 365] \sum_{i=1}^{4} A_i C_i \\ &= \text{BR}\ Q_0 \sum_{i=1}^{4} A_i C_i \end{aligned} \tag{1}$$

where $Q_0 = 1.945 \times 10^{10}$ and A_i is the activity (in pCi/L) for each of the nuclides in the table above, C_i is its dose coefficient in Sv/Bq, and we recognize the product in brackets as the number of minutes per year. If the progeny were in equilibrium with each other then $A_i = A_1$ (all have the same activity as the parent). Much more commonly the progeny are split off using the equilibrium factor f_{eq}, as shown:

$$A_i = \begin{cases} A_1 & i = 1 \quad \text{(parent)} \\ \text{f}_{eq} A_1 & i = 2, 3, 4 \quad \text{(progeny)} \end{cases} . \tag{2}$$

Then the dose becomes

$$D \simeq \text{BR}\ Q_0\ A_1 \left(C_1 + f_{eq} \left[C_2 + C_3 + C_4 \right] \right) . \tag{3}$$

Clear visual confirmation of a reduced equilibrium factor (due to removal of progeny onto surfaces) is shown in Fig. 3.

Occasionally C_1 is ignored since it is small (only a few percent of the dose comes from radon itself). Doing this, we find a compact form for the radon dose including its progeny using *only* the concentration in pCi/L for ^{222}Rn:

$$D_{prog} \simeq \text{BR}\ Q_0\ A_1 f_{eq} \left(C_2 + C_3 + C_4 \right) \tag{4}$$

where we have added the subscript *prog* to show that progeny are explicitly included.

It is also common to give a 'one-shot' dose expression for radon. The ICRP gives a current dose coefficient (see also [4]) D_0 = 6.9 nSv/(Bq-h/m^3) using an 'equilibrium factor' of 0.4. Unlike the previous route, which entailed identifying the volume of inhaled radioactivity, the ICRP coefficient already makes assumptions about average breathing rates and is based simply on the radioactivity concentration (in Bq/m^3). The inhaled radon radiation dose is written

$$D_{1-shot} = D_0 \times S \left[\text{Bq/m}^3\ \text{T (h)} \right] \tag{5}$$

where D_0 is given above, *tacitly using* $f_{eq} = 0.4$. Here S is the total exposure over T hours to a known radioactivity concentration in

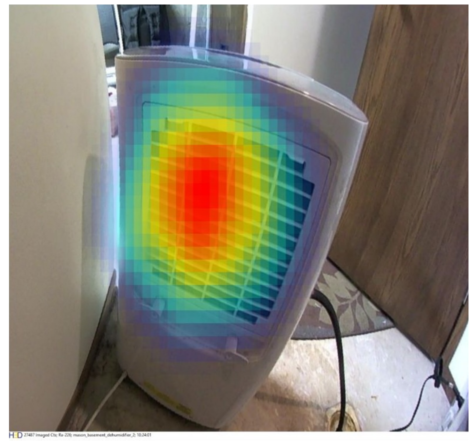

Figure 3: Gamma emissions from decay of 'plated out' radon progeny, courtesy of Jim Mason of H3D. (A precisely similar effect occurs on blades in small fans in mines, reported by Holub et al. [3].) This is a model H420 10.5 hour gamma ray image of a basement dehumidifier running continuously (with filter cleaning) for 7 years. (Had it been a *humidifier*, the charged species would have been neutralized quickly.) Measurements of 26-42 pCi/L dropped to 1.2 pCi/L after mitigation.

Bq/m^3. To neatly compare with the full dose expression in Eq. 4 we write S for one year as

$$S = A_1 \times 0.037 \text{ Bq/pCi} \times 1000 \text{ L/m}^3 \times \text{hrs/year} \quad (6)$$

with A_1 in pCi/L.

We assume a breathing rate of 10.7 L/min and

- an *outdoor* radon level of 0.4 pCi/L and f_{eq} = 0.6 outdoors
- an *indoor* (radon-mitigated) radon level of 1.5 pCi/L and f_{eq} = 0.4 indoors

and find doses in mSv = 1000 μSv as shown in Table 2.

source	*dose source*	*dose* (1 y)
radon (indoor)	DOE prog	2.96
radon (indoor)	ICRP 1-shot	3.35
radon (outdoor)	DOE prog	1.18
radon (outdoor)	ICRP 1-shot	1.34
background	direct measurement	1.23

Table 2: 1-year radiation effective doses in mSv from inhalation of indoor and outdoor radon and from background radiation (gamma rays from soil radionuclides + cosmic rays). Indoor radon value assumed as 1.5 pCi/L, outdoor as 0.4 pCi/L. Background is assumed measured outdoors.

We can explicitly compare doses in μSv per year, noting that both expressions have a number of factors in common, which we cancel. We find

$$\text{BR} \times 60 \times f_{eq} \times 0.0237 = 6.9$$

must hold for the two expressions to agree. Assuming f_{eq}=0.4 (as mentioned for D_{1-shot}) requires BR = 12.1 L/minute, quite close to the assumed breathing rate of 10.7 L/min made earlier. Thus we conclude that the ICRP 1-shot dose expression agrees very well with the somewhat more involved DOE-used data [5].

$$D_{prog} = 460.9 \text{ BR A}_{\text{Rn}} \times f_{eq} \quad (7)$$

$$D_{1-shot} = 2236 \text{ A}_{\text{Rn}} \times \frac{f_{eq}}{0.4}. \quad (8)$$

The point of these is that, while the ICRP is the source of almost all dose coefficients for all radionuclides, slight modifications to assumptions about breathing rates, for example, can give rise to somewhat different doses.

By chance, around Rocky Flats (Arvada, CO) annual doses from background radiation and from outdoor radon are comparable. The doses are for 100% outdoor occupation. In fact, significant time spent indoors will *lower* background exposure (from shielding by building materials) and *raise* radon exposure (which can be 10-20 times higher in unmitigated buildings). Thus it is fair to say that the yearly radiation dose due to radon is distinctly higher than from background, since the Front Range of Colorado has among the highest levels of background radiation in the U.S. (high altitude, thus more cosmic rays, and plenty of natural soil radioactivity).

Generally speaking background radiation doses worldwide (annual doses of about 2,400 μSv = 2.4 mSv) per year (apart from a handful of 'high natural background areas' where annual doses are 260 mSv) are believed to have no health impacts, and outdoor levels of radon about 0.4 pCi/L are regarded as safe. By contrast, the EPA recommends radon mitigation for steady radon levels above 4 pCi/L.

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dehumidifier, graphically illustrating the significance of the "equilibrium factor" in the text.

References

[1] IRSN (France). "New dose coefficients for radon. recommended in ICRP Publication 137 Explanatory note". In: *Report PSE-DSNTE/2018-00002* (2018). URL: https://en.irsn.fr/sites/en/files/2023-12/IRSN_Report-PSE-SAN-2018-00002_Radon-dose-coefficient.pdf.

[2] Jing Chen. "RISK ASSESSMENT for RADON EXPOSURE in VARIOUS INDOOR ENVIRONMENTS". In: *Radiation Protection Dosimetry* 185.2 (2019), pp. 143–150. ISSN: 17423406. DOI: 10.1093/rpd/ncy284.

[3] Robert F Holub et al. "The reduction of airborne radon daughter concentration by plateout on an air mixing fan". In: *Health Physics* 36.April (1979), pp. 497–504. URL: https://www.aivc.org/sites/default/files/airbase_521.pdf.

[4] J. D. Harrison and J. W. Marsh. "ICRP recommendations on radon". In: *Annals of the ICRP* 49.ICRP 2019 Proceedings (2020), pp. 68–76. ISSN: 1872969X. DOI: 10.1177/0146645320931974.

[5] Richard W Leggett and Michael B Bellamy. *RADON CANCER RISK COEFFICIENTS and AGE-SPECIFIC EFFECTIVE DOSE COEFFICIENTS*. Tech. rep. January. Oak Ridge National Laboratory, 2017. URL: https://rais.ornl.gov/documents/RadonDoseandRiskCoefficientReport.pdf.