A REVIEW OF FACTORS AFFECTING INDOOR LEVELS OF RADON AND ITS PROGENY

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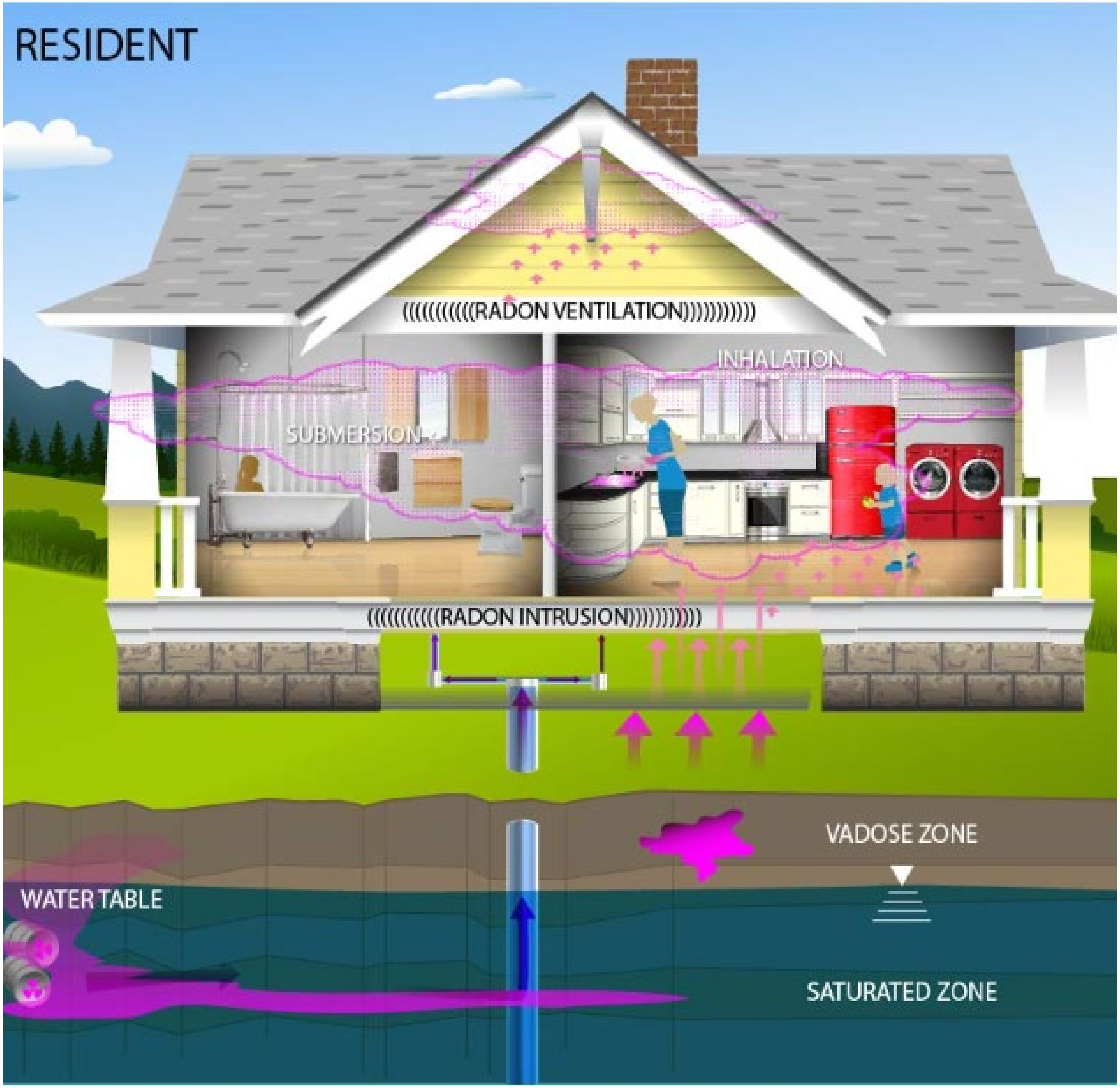

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LIST OF ABBREVIATIONS

ACH	Air Exchange per Hour
A_{eq}	Activity Equilibrium Factor
AQI	Air Quality Index
ARAR	Applicable or Relevant and Appropriate Requirement
Bq/m^3	Becquerels per Cubed Meter (Global Usage)
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
ELCR	Excess Lifetime Cancer Risk
F_{eq}	Radon Indoor Fractional Equilibrium Factor
ICRP	International Commission on Radiological Protection
NIOSH	National Institute for Occupational Safety and Health
pCi/L	Picocuries per Liter (United States Usage)
PRG	Preliminary Remediation Goals
Rn-219	Radon-219 (Actinon)
Rn-220	Radon-220 (Thoron)
Rn-222	Radon-222 (Radon)
RVISL	Radon Vapor Intrusion Screening Level
US EPA	United States Environmental Protection Agency
WL	Working Level

GLOSSARY

Activity Equilibrium Factor (A_{eq}): US EPA RVISL user guide defines this as "the ratio of progeny to parent activity concentrations at a given air exchange rate".

Air Quality Index (AQI): "an index for reporting daily air quality. It tells you how clean or unhealthy your air is, and what associated health effects might be a concern. The AQI focuses on health effects that you may experience within a few hours or days after breathing unhealthy air. The AQI is calculated for four major air pollutants regulated by the Clean Air Act: ground level ozone, particle pollution, carbon monoxide, and sulfur dioxide. For each of these pollutants, US EPA has established national air quality standards to protect public health" (US EPA, 2014a, Pg. 2).

Alpha Radiation: Radiation consisting of helium nuclei (two neutrons and two protons) that are discharged by radioactive disintegration of some heavy elements, including radon.

Applicable requirements: Cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental, state environmental, or facility siting laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance found at a CERCLA site. Only those state standards that are identified by a state in a timely manner and that are more stringent than federal requirements may be applicable.

Bronchial Dose: The concentration to cell nuclei in the bronchial airways from the inhalation of Rn-222, Rn-220, and/or Rn-219 decay products.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA): Issued in 1980, it is The United States Federal Superfund law that established the federal Superfund program under the Environmental Protection Agency.

Emanation Rate: The number of radon atoms that are produced from a mineral grain into the pore space per a unit of time. It also characterizes the behavior of radon in soil and rock minerals.

Excess Lifetime Cancer Risk (ELCR): The probability of cancer development resulting from the exposure to a carcinogen such as radon.

Exhalation Rate: The number of radon atoms that move through the pore space and escape into the atmosphere.

Preliminary Remediation Goal (PRG): The average concentration of a certain isotope per a defined area of exposure that determines the targeted risk for an individual who is exposed at random.

Radon Indoor Inhalation Fractional Equilibrium Factor (F_{eq}): A unitless disequilibrium ratio of measured radon gas progeny alpha emissions at equilibrium in a specified volume.

Relevant and appropriate requirements: Cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental or state environmental or facility siting laws that, while not ‘‘applicable’’ to a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance at a CERCLA site, address problems or situations sufficiently similar to those encountered at the CERCLA site and their use is well suited to the particular site. Only those state standards that are identified in a timely manner and are more stringent than federal requirements may be relevant and appropriate.

Unconventional Wells: Wells drilled using hydraulic fracturing to access crude oil and natural gas.

Working Level (WL): Any combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of alpha particles with a total energy of 130 billion electron volts.

ABSTRACT

With radon and its daughter products acting as the second leading cause of lung cancer, it is imperative to monitor their presence inside commercial, community, and residential dwellings. The radon indoor inhalation fractional equilibrium factor (F_{eq}) is a unitless disequilibrium ratio of measured radon gas to its progeny alpha emissions at equilibrium in a specified volume. Within the past 30 years, a well-rounded understanding of how air exchange rates affect this equilibrium factor has developed, leading to the creation of a radon vapor intrusion screening level (RVISL) calculator by the United States Environmental Protection Agency (US EPA). The goal of the calculator is "to assist risk assessors, remedial project managers, and others involved with risk assessment and decision-making at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites in developing RVISLs or preliminary remediation goals (PRGs) for indoor Rn-222, Rn-220, and Rn-219 that are risk or dose based" (US EPA, 2019, Pg. 1). In an effort to advance the risk assessment science of the various Radon isotopes, a closer look at the impact of factors such as exhalation, solid-particle concentration, surface deposition, and air quality is necessary. In this review, studies regarding the influence of these factors were summarized to provide a more comprehensive approach in establishing risk assessment for public health.

INTRODUCTION

Radon-222 (Rn-222) is the first progeny of Radium-226 decay (Nero et al., 1990, Pg. 14). Found commonly in bedrock, soil, and even groundwater with trace concentrations of Uranium-238, Rn-222 and progeny can be released from radioactive ore in these sources (Nero, et al, 1990, 15-16). In process of emanation and exhalation, these vapors can enter indoor spaces by way of natural occurrences like wind or transference from particle deposition. Emanation rate can be defined as the number of radon atoms that are produced from a mineral grain into the pore space per a unit of time (Collé et al,, 1981, Pgs. 5-6). While emanation does occur, most radon atoms do not make it out of the ore material into the interstitial space. Because of the exceedingly small diffusion coefficient through dense minerals, even fewer atoms are likely to be exhaled to the atmosphere. The emanated product is then quantified using exhalation rate, which is the number of radon atoms that move through the pore space and escape into the atmosphere. Both emanation and exhalation rates also characterize the behavior of radon in soil and rock minerals; however, neither is normalized based on pore size, mass, or concentration (Collé et al., 1981, Pg. 6). For the purposes of this project, radon also includes Radon-220 (Rn-220) and Radon-219 (Rn-219). Rn-220, known commonly as thoron, is a progeny of Thorium-232, while Rn-219, also referred to as actinon, is a daughter product in the decay of Actinium-227. All three are colorless, odorless, and nonreactive, which is characteristic of noble gases. If the specific radon isotopes act differently to the environmental conditions discussed, a differentiation will be made.

An understanding of the radioactive chain of decay is necessary in assessing the risk that short-lived radon progeny can have on public health and the environment. Comparatively, radon toxicity and dosimetry are less than that of its short-lived decay products, contributing to radon as the second leading cause of lung cancer in the United States (Carmona, 2005, Pg. 1). The cancer risk and bronchial dose can be attributed to progeny from the radon chain of decay depositing onto lung tissue and emitting harmful working levels (WLs) of radioactive alpha particles. According to the US EPA's Code of Federal Regulations, a working level is defined as a combination of short-lived radon decay products per liter of air resulting in a total emission of alpha particles with energy equaling that of 130 billion electron volts (US CFR, 2022). Specifically, WLs do not include the contribution from the parent. In the case of Rn-222, only progeny prior to Pb-210 are included; Pb-210 has a 22.3-year half-life and will not be airborne to continue generating progeny available for inhalation. For Rn-220 and Rn-219 all progenies are included. Contributing to these WL calculations is the time in which decay occurs. Rn-222 has a 3.89-day half-life. Rn-220 has a 56-second half-life, and Rn-219 has a 3.96-second half-life. Rn-220 has Lead-212 (Pb-212) as a progeny with a notably longer half-life of 10.6 hours; however, all the Rn-220 progeny are included in radon indoor inhalation fractional equilibrium factor (F_{eq}) and WL calculations. (Chege et al., 2019, Pgs. 1-2).

INDOOR INHALATION FRACTIONAL EQUILIBRIUM FACTOR (F_{eq})

The radon indoor inhalation fractional equilibrium factor (F_{eq}) is defined as the unitless disequilibrium ratio of measured Rn-222, Rn-220, or Rn-219 gas progeny alpha emissions to total progeny alpha emissions at equilibrium in a specified volume and is quantified as seen in equation 1, where i is representative of an undetermined rate of air exchange (Asano et al., 2020, Pg. 2).

$$\text{Eq 1} \qquad (F_{eq})_i = \frac{Total\ Progeny\ Alpha\ Energy\ Emitted\ (MeV)}{Total\ Progeny\ Alpha\ Energy\ Emitted\ at\ Equilibrium\ (MeV)}$$

At equilibrium in an enclosed space with no ventilation, the value of the F_{eq} is equal to one; however, an F_{eq} of one is seldom measured due to conditions such as atmospheric and meteorological changes, building and natural materials, air exchanges and quality, particle deposition on surfaces and aerosols, and more (US EPA, 2019, Pg. 12). To mitigate both long- and short-term exposure in dwellings and public spaces, risk assessments for public health have been conducted to determine the indoor (F_{eq}) and appropriate WLs of Radon and its progeny. Currently, the RVISL calculator accounts for WL conversions to indoor air concentrations in picocuries per Liter (pCi/L) by applying the following conversions as seen in equations 2, 3, and 4 below (US EPA, 2019, Pgs. 12-13).

$$\text{Eq 2} \qquad WL\ (Rn-222) = C_{i,a}\left(\frac{pCi}{L}\right) \times \left(\frac{F_{eq}\times 1WL}{\left(\frac{100pCi}{L}\right)}\right)$$

$$\text{Eq 3} \qquad WL\ (Rn-220) = C_{i,a}\left(\frac{pCi}{L}\right) \times \left(\frac{F_{eq}\times 1WL}{\left(\frac{7.5pCi}{L}\right)}\right)$$

$$\text{Eq 4} \qquad WL\ (Rn-219) = C_{i,a}\left(\frac{pCi}{L}\right) \times \left(\frac{F_{eq}\times 1WL}{\left(\frac{162pCi}{L}\right)}\right)$$

The RVISL has the capability of calculating the radon progeny concentrations in the air, based on mathematical calculations of hourly air exchange rates (ACH) and the decay rates of the chain members, called the activity equilibrium factor (A_{eq}) (US EPA, 2019, Pgs. 39-41). The purpose of this project is to determine if additional mathematical models, based on other contributing factors, can be applied to the RVISL to predict the A_{eq} with greater accuracy. According to US EPA's RVISL user guide, the F_{eq} acts as a conversion factor to determine local, state, federal, and international compliance with WL-based applicable or relevant and appropriate requirements (ARARs) issued under the Uranium Mill Tailings Radiation Control Act (UMTRCA) in addition to risk-based limits and dose-based limits that are ARARs (US EPA, 2019, Pgs. 11-12). Table 1 presents current suggested indoor concentrations limits from several regulatory agencies and the RVISL calculator. Of the three radon isotopes, there is no current UMTRCA standard for Rn-219; however, for Rn-222 and Rn-220, the standard of 0.02 WL is used as an ARAR, and previously an assumed F_{eq} of 0.4 (40%) for Rn-222 and 0.02 (2%) for Rn-220 is used. When applying these standards to equations 2 and 3, the ARAR compliance level based on radon was 5 pCi/L or 187 Bq/m3 for Rn-222 and 7.5 pCi/L or 277.5 Bq/m3 for Rn-220 (US EPA, 2019, Pg. 12), although that has been superseded with the issuance of the RVISL[1]. It is well understood that the F_{eq} is largely influenced by ventilation as air exchanges in a complete renewal of air. Lesser studied

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[1] See the transmittal memo "transmittal memo Distribution of the Superfund Radon Vapor Intrusion Level Electronic Calculator" at https://semspub.epa.gov/work/HQ/100002886.pdf.

factors also can include air quality, geogenic controls, exhalation, solid particle deposition, and even surface deposition.

Table 1. Summary Statistics of Current Suggested Indoor Concentrations Limits and Equilibrium Factors (F_{eq}) of Rn-222, Rn-220, and Rn-219

Source	**RADON (RN-222)**			**THORON (RN-220)**			**ACTINON (RN-219)**		
	Concentration (pCi/L)	Concentration (Bq/m3)	F_{eq}	Concentration (pCi/L)	Concentration (Bq/m3)	F_{eq}	Concentration (pCi/L)	Concentration (Bq/m3)	F_{eq}
US Environmental Protection Agency (US EPA)[a]	4	60	0.4	7.5	-	-	-	-	-
Uranium Mill Tailings Radiation Control Act (UMTRCA)[b]	5	185	0.4	7.5	277.5	-	-	-	-
International Commission on Radiological Protection (ICRP) Indoor Standard[c]	5.405	300	0.4	2.703	100	0.1	2.703	100	-
National Council on Radiation Protection and Measurements (NCRP)[d]	8±2	296±74	0.4-0.5	-	-	-	-	-	-
National Institutes of Standards and Technologies (NIST)[e]	2-4	-	0.5	-	-	-	-	-	-
Oak Ridge National Laboratory (ORNL) Resident[f]	-	-	0.8899	-	-	0.2106	-	-	0.8569

Source	**RADON (RN-222)**			**THORON (RN-220)**			**ACTINON (RN-219)**		
	Concentration (pCi/L)	Concentration (Bq/m3)	F_{eq}	Concentration (pCi/L)	Concentration (Bq/m3)	F_{eq}	Concentration (pCi/L)	Concentration (Bq/m3)	F_{eq}
Oak Ridge National Laboratory (ORNL) Commercial[f]	-	-	0.7209	-	-	0.5227	-	-	0.6379
United Nations Scientific Committee on The Effects of Atomic Radiation (UNSCEAR)[g]	-	-	0.2	2	74	0.02	-	-	-
World Health Organization (WHO)[h]	2.703	100	-	-	'	-	-	-	-
European Environment & Health Information System (ENHIS)[i]	1.081	40	-	-	-	-	-	-	-

Values come from: [a]US EPA, 2016, p. 12; [b]US EPA, 2014b, p. 18 conversion of 0.02 WL; [c]Lecomte et al., 2014; [d]National Research Council (US), 1999; [e] Collé et al., 1981; [f]Asano et al., 2020; [g] UNSCEAR, 2000; [h]WHO, 2010; [i]ENHIS and WHO, 2005.

VENTILATION, AIR EXCHANGE, AND FLOW RATE

Air exchange is dependent on elevated levels of ventilation for enclosed spaces. Prior to the 1980s, the average ventilation rate for a dwelling was higher, meaning faster complete air exchange, with both residential and commercial spaces defined as leaky from macroporous gaps in foundation and other building materials allowing greater air flow (Collé et al., 1981). As building standards tightened with a greater prevalence of HVAC systems, mechanical ventilation has been suggested to maintain and/or improve air exchange rates; however, the use of central heating and cooling units contributes to an increased F_{eq} that can be seen in Table 2 (Collé et al., 1981, Pgs. 51-72). In a pressure-driven flow of 1000 pCi/hr(m2), radon concentrated soil gas permeates cracks, gaps, and fractures of home foundations similarly to how it emanates from rock (Nero et al., 1990, Pg. 5). This pressure gradient, coupled with warmer, thinner air of a dwelling, allows for more rapid intrusion into indoor spaces. While Rn-222 has a natural emanation rate of between 10 and 100 pCi/hr(m3), increasing the flow rate can drive the concentration to upwards of 3000 pCi/m3 (Kusudaet al., 1980, Pgs. 1203-1205). Rn-220, which has the highest natural emanation rate, is relatively unaffected by increased flow rate, reaching 300 pCi/m3 maximum concentration (Kusuda et al., 1980, Pgs. 1203-1205). Overall, F_{eq} and WLs for Rn-222 have an F_{eq} of 0.32, which is lower than the 0.4 F_{eq} suggested by the International Commission on Radiological Protection (ICRP), during hours of peak movement from 6 A.M. to 4 P.M. and lower than the 0.87 F_{eq} during inactive hours (Vaupotič & Kobal, 2001, Pg. 359). These values are reflected in Tables 3 and 2, respectively. In addition, with a greater flux of people in and out of a dwelling during these periods of work, school, or recreation, the air exchange rate also improves due to open windows and doors, greater area, and more furnishings for particle deposition (Vaupotič & Kobal, 2001, Pg. 362). The effects of peak activity hours on Rn-220 and Rn-219 is not comprehensive.

Table 2. Factors Increasing Indoor Rn-222 F_{eq}

Factor Type	F_{eq}	Reference
Smoking	0.72	US EPA, 2004, Pgs. 18-25
High Altitude	0.71	Chen & Harley, 2018, Pg. 493-495
Humidity/Rain	0.69 ± 0.18	Acree, 2014, Pgs. 3-5
Smog	0.63 ± 0.15	Chambers et al., 2015, Pgs. 1178-1180
Tighter Construction (concrete, brick, etc.)	0.60 ± 0.24	Collé et al., 1981
Inactivity (4:00 P.M. to 6:00 P.M.)	0.59	Kusuda et al., 1980, Pgs. 1203-1204
High Population Density (greater than or equal to 300 persons/km^2)	0.58	Chen & Harley, 2018, Pg. 492
Increased Emanation Rate	0.56	Kusuda et al., 1980, Pgs. 1202-1205
Underground Workspaces	0.54	Kreuzer and McLaughlin, 2010, Subsection "Health Effects"
Suggested Average Limit	0.4	US EPA, 2004, Pgs. 1&3

*Table 2 exhibits factors that increase the F_{eq} of Rn-222. While minimal data is presented in literature, it is understood that these increases are representative of Rn-220 and Rn-219, as each factor listed increases the incident equilibrium.

Table 3. Factors Decreasing Indoor Rn-222 F_{eq}

Factor Type	F_{eq}	Reference
Hours of High Activity (6:00 A.M. to 4:00 P.M.)	0.27-0.78	Chen & Harley, 2018, Pgs. 493-495
Thermal Spas	0.3	Chen & Harley, 2020, Pg. 345
Sea Level Altitude	0.31 ± 0.09	Nero et al., 1990, Pgs. 60-66
Snow Coverage	0.32	Yamazawa et al., 2005, Pg. 2
Ventilation (open windows, minimal HVAC use, greater sq. ft., etc.)	0.33	Chen & Harley, 2018, Pgs. 493-495
Sparse Population Density (less than or equal to 90 persons/km^2)	0.34 ± 0.12	Chen & Harley, 2018, Pg. 492-493
Loose Construction (wood, gapping, lack of insulation, etc.)	0.36	Collé et al, 1981 and Appleton & Miles 2010, Pgs. 802-803
Tourist Mines and Show Caves	0.39	Chen & Harley, 2020, Pg. 343
Aerosol Particle Plate Out/Deposition	0.39 ± 0.04	Harley et al., 2012, Pgs. 461-462 and Porstendörfer et al.1978, Pgs. 468-472
Suggested Average Limit	0.4	US EPA, 2004, Pgs. 1&3

*Table 3 exhibits factors that decrease the F_{eq} of Rn-222. While minimal data is presented in literature, it is understood that these increases are representative of Rn-220 and Rn-219, as each factor listed increases the incident equilibrium

AIR QUALITY AND CLIMATE-DRIVEN FACTORS

According to the United Nations' 6th Intergovernmental Panel on Climate Change Assessment of 2021, the cumulation of CO2 emissions has increased the global surface temperature 1.1°C since the nineteenth century and further worsened air quality (IPCC, 2021, Pg. 8). One of the factors responsible is smog. In densely populated areas, such as large urban sites and primarily industrial regions, the prevalence of smog in conditions like thermal inversions can result in a decrease in atmospheric air exchanges, causing progeny to plate out onto the gaseous air particles without clean air dilution, which then enter indoor settings (Chambers et al., 2015, Pg. 1). To understand the impact, healthy ambient air has a limit of roughly 0.08 ppm of ozone (US EPA, 2021, Pg. 1), 35 ppm of CO (US EPA and NIOSH, 2022), and 100 ppb NO2 per 1 hour (US EPA, 2018), with anything outside of this range being considered a PRG. In areas of heavy smog, the air quality is decreased due to the recycling of the gaseous particle-rich air that causes these concentrations and the overall F_{eq} to surpass suggested limits. While these air pollutants pose their own issue, radon, thoron, and actinon plate onto these particles, further increasing the excess lifetime cancer risk (ELCR) due to heightened bronchial dosage from alpha decay emission. Depending on air quality index (AQI), smog with an AQI above 30 can increase the deposition of Rn-222 between 6.6 ppb and as much as 12.4 ppb, increasing ELCR as seen in Western Sydney, New South Wales, Australia in a 5-year study of continuous hourly surface atmospheric radon measurements (Chambers et al., 2015, Pg. 1776). This equates to an increase in F_{eq} between 0.48 and 0.79, depending on the magnitude of pollution, as reflected in Table 2.

An additional contributor to Rn-222 and Rn-220 prevalence indoors is smoking. According to the World Health Organization (WHO), smokers and ex-smokers have a substantially higher risk of developing radon-induced lung cancer than non-smokers (WHO, 2010, Pg. xxi). The risk of Rn-222 and Rn-220 concentrations associated with a lifetime of smoking, classified as greater than or equal to 15 cigarettes per day, is a 16% per 100 Bq/m3 or 2.6 pCi/L increase (WHO, 2010, Pg. xxi). The concentration of Rn-222 that it takes for this increase in ELCR is only 6.7 Bq/m3 or 0.18 pCi/L for chronic smokers and a much larger 167 Bq/m3 or 4.51 pCi/L for lifelong nonsmokers (WHO, 2010, Pg. xxi). For a lifelong nonsmoker, the comparative risk concentration is reduced ten times compared to that of chronic smoker. For each cigarette smoked daily or from which smoke is inhaled second hand, there is a 0.01 pCi/L or 0.37 Bq/m-3 increase for up to 15 cigarettes (WHO, 2010, Pg. xxi). Anything more is accounted for in the values provided for chronic smoking. These increases in Rn-222 concentration are reflected in increased F_{eq}, as seen in Table 2. The RVISL calculator results may greatly underestimate the ELCR for smokers and those who live in smog-prone regions of the country.

BIOGEOCHEMICAL FACTORS

Environmental factors such as precipitation, elevation and pressure, and exhalation contribute to radon vapor intrusion. Rain disrupts the natural ordering of soil and can lead to corrosion of bedrock, which releases radon that was trapped in an inert gaseous state (Acree, 2014, Pg. 5). This disturbance increases the concentration of free radon from emanation, beginning its chain of decay, and increasing the F_{eq} in relation to the US EPA and NIST suggested limit of 0.4 (Yazzieet al., 2020, Pg. 4). This is reflected in Table 2. In a study that examined HVAC and rain on Rn-222 concentrations, the overall average of a full day of rain with no HVAC usage and high barometric pressure was 6.9 pCi/L or 255.3 Bq/m3, well over the suggested limit of 4 pCi/L in the study and 5 pCi/L, according to US EPA (Aree, 2014, Pg. 4). Conversely to rain, and despite cold temperatures increasing F_{eq} values due to a greater pressure difference between indoors and outside, snow acts as a passivating layer for the ground (Yazzie et al., 2020, Pg. 3). This prevents bedrock, soil, and groundwater disruption from other forms of precipitation and avoids the permeation of radon out of these sources. According to the National Weather Service and the National Institute of Standards and Technology (NIST), when an average of 3-5 inches of snow fall, Rn-222 WLs and overall F_{eq} decreases to 0.34, as seen in Table 3. This is roughly 12% less risk than the suggested limit of 0.4, which is the action level of 148 Bq/m3 (Yazzie et al., 2020, Pgs. 12-13 and 15). As climate change progresses, with both flooding and draught becoming more prevalent, the acidity of land and water increases. In these acidic environments, the environmental pH has both corrosive and erosive effects on rock bodies, soil, and ground surfaces, releasing newly reactive radon and ultimately contributing to a higher F_{eq}, as seen in Table 2 (Chen, and Harley, 2018, Pg. 493).

Exhalation closely mirrors the permeation of radon from ground surfaces; however, it also represents the release of Rn-222 from building materials (Collé et al., 1981, Pg. 6). Crystal structure, such as short-range order and overall porosity of a material, affects the intrusion of radon into dwellings, such that brick and concrete with larger pores but poor permeability increase the working levels of radon and its progeny. Wetting of materials such as concrete or drywall can dampen the concentration of Rn-222 and its daughters, due to the ability of the moisture to fill in gaps (Collé et al., 1981, Pgs. 36-37 and 41). Values for how building materials affect construction and overall F_{eq} can be found in Tables 2 and 3. In conjunction with permeability, groundwater also acts as a common source of exhalation due to the short distances traveled and the closed systems used by public works and well systems. This acts as a source of radon ingestion but is not as prevalent or as high risk as inhalation.

UNDERGROUND SPACES

It is well-known that there is an increased risk of lung cancer incidence associated with mining, resulting from higher concentrations of radon progeny. Additionally, many studies have shown that there is a direct relation to Rn-222 and Rn-220 alpha emissions as the exposure from the increased emanation rate is present (Chen & Harley, 2020, Pgs. 343-345). This increased emanation rate is a result from the disruption of the rock bodies as they are extracted, releasing previously inert radon gases. Mining, especially of certain metal ores like uranium, increases bronchial dosage by upwards of 15% due to the absence of ventilation and increased emanation rates. A sample uranium mine in Kosovo showed concentrations of Rn-222 were as high as 441 Bq/m3 with an average of 286 Bq/m3 (Margineanu, 2019, Pgs. 050004-2). Studies have not examined the impacts on concentrations or F_{eq} for Rn-220 or Rn-219, but the increase in F_{eq} for Rn-222 can be seen in Table 2. Similar to mining, hydraulic fracturing for oil and other deeply buried resources increases the concentration of radon past suggested limits. According to a study in Pennsylvania, during a period of growth in hydraulic fracturing, 7,469 unconventional wells were drilled (Casey et al., 2015, Pg. 1130). Buildings within 20 km of a well site had an average Rn-222 concentration of 8.4 pCi/L or 310.8 Bq/m3, which was roughly 42% greater than the suggested limit by US EPA (Casey et al., 2015, Pgs. 1130 and 1132).

Mines and unconventional wells are not the only underground spaces impacted by high Rn-222, Rn-220, or Rn-219 concentrations. Caves, tourist mines, and thermal spas contain a wide range of concentrations, some exceeding suggested limits of all governing bodies listed in Table 1. In the Pleistocene cave at Petralona in Halkidiki, Northern Greece, Rn-222 concentrations reached seasonal peaks of up to 22,420 Bq/m3 or 605.95 pCi/L, which is 73 times the highest limits suggested by the National Council on Radiation Protection and Measurements (NCRP). The study suggests these unparalleled concentrations result from rapid exhalation rates through cracks, gaps, and pores with minimal air exchange (Margineanu, 2019, Pgs. 050004-2). In a different study of the Polovraci Cave in Romania, mean concentrations of Rn-222 were 1,929.5 Bq/m3 or 52.15 pCi/L, which is 6.43 times greater than the NCRP suggested limits. While these are lower concentrations than the Greek cave in the previous study, the bronchial dose and ELCR are higher than suggested (Margineanu, 2019, Pgs. 050004-4). These environments represent closed systems; however, underground spaces like show caves and tourist mines have a greater rate of air exchange in more open systems, leading to an Rn-222 F_{eq} of 0.39, which is lower than the suggested US EPA and NIST limits (Chen & Harley, 2020, Pg. 343). Thermal spas are less understood, where certain areas contribute Rn-222 concentrations as high as 496,000 Bq/m3 or 13,405 pCi/L due to outgassing, increased exhalation rates, and poor air exchange (Chen & Harley, 2020, Pg. 345). In some areas with high humidity, the concentrations can be as low as 91 Bq/m3 where gaseous particles are attracted to large precipitates. Overall, thermal spas also have a lower than suggested limit, with an average Rn-222 F_{eq} of 0.30 as seen in Table 3 (Chen & Harley, 2020, Pgs. 345-346). There is minimal data to support any claims regarding Rn-220 or Rn-219; however, levels of Radium (Ra-226) are well studied and often exceed suggested limits as well.

SOLID PARTICLE CONCENTRATION AND SURFACE DEPOSITION

As Rn-222, Rn-220, and Rn-219 decay, they transition from a gas to solid particles as the progeny are produced (Kusuda et al., 1980, Pg. 1201). These radioactive solid particles can aggregate or bind to aerosols, which then are inhaled and can attach to bronchial tissue, increasing the risk of tissue damage from the radioactivity present. A study in Brittany, France, showed that over time, as these aerosols bind with free-floating progeny, there is an increase in bronchial dose (Huet et al., 2001, Pg. 557). Bronchial dose can be defined as the calculable deposition on bronchial epithelial tissue in the lungs of alpha decay products from the radioactive progeny (Chen & Harley, 2018, Pgs. 490-491). In the same French study, it was determined that due to low air exchange of 0.15 h^{-1} and a linear sloping trend of particle concentration over time, the F_{eq} was as low as 0.16, well below the suggested 0.4 limit (Huet et al., 2001, Pgs. 556-557). This is due to the attachment of Rn-222 and Rn-220 progeny to the aerosols and the deposition or plating out onto surfaces (Huet et al., 2001, Pgs. 557-558). Unlike the higher risk incurred when daughter products adhere to smog and smoke, deposition onto solid or liquid surfaces reduces the overall bronchial dose rate, as it is removed from the breathable air.

In a moderately ventilated room containing furniture at 200 and 600 m/h-1, the average deposition rate was 0.1 particles/h-1 for radon progeny (Porstendörfer, 1994, Pg. 235). In a well-ventilated space that was well furnished, the deposition rate increased to 0.18 particles/h-1, which indicates that plate out decreases the F_{eq} greatly, as airborne particles are no longer free in space (Porstendörfer, 1994, Pgs. 235-238). The opposite can be seen when clean rooms of laboratories undergo an increased equilibrium factor for radon and its progeny, due to fewer surfaces where deposition can occur and fewer freely detached radon progeny (Chen & Harley. 2018, Pg. 494). In areas with a greater number and variety of surfaces, such as schools, doctors' offices, courtrooms, or stores, rates of deposition and F_{eq} improve, minimizing the effects of free-floating daughter products for inhalation (Chen & Harley, 2018, Pg. 494). This can be seen in Tables 2 and 3.

CONCLUSION

While the US EPA's RVISL calculator applies a mathematical model to predict theoretical maximum indoor F_{eq} values based on air exchange rates, there are additional factors that can significantly impact the airborne concentrations of radon progeny. Results of this project show that air exchange is the greatest factor in impacting the indoor radon F_{eq}, but other factors may contribute enough to bear consideration. Based on the studies included, analyzing the factors that increase Rn-222, Rn-220, and Rn-219 progeny concentrations can identify problem areas not previously addressed by the RVISL calculator. The largest increases in radon indoor fractional equilibrium are from smoking. Homes and establishments with cigarette smoking have more radon and progeny in the air, increasing Rn-222 F_{eq} to 0.73 and increasing the associated risk. Further analysis shows that the F_{eq} increases by 55 percent compared to the 0.4 F_{eq} suggested by the US EPA. This value is based on smoking rates of more than 15 cigarettes per day. As stated, non-smokers experience ten times less risk than a chronic smoker. Similarly, this study shows that homes in smog-dense areas have greater concentrations of radon and progeny in the air, increasing the indoor Rn-222 F_{eq} and the ELCR by 57.5 percent, with an F_{eq} of roughly 0.63. Further analysis shows that the indoor radon inhalation F_{eq} increases an additional 20 percent based on smog rates with an AQI greater than 300. Other biogeochemical impacts show that homes experiencing high levels of precipitation also have an increased Rn-222 F_{eq} of 0.47. Further analysis shows that the indoor F_{eq} increases by 18 percent based on water saturation levels of soil above 0.3 L/kg of soil. Other factors that increase the F_{eq} are underground workspaces, especially uranium mines and structures with tighter construction and less permeable materials, higher altitudes, greater population density, hours of inactivity, and greater emanation and exhalation rates, as seen in Table 2. These factors largely contribute to reduced air exchange, or decreased particle deposition, due to things like air thickness and pollution. The general trends are well studied for Rn-222 and can be applied to Rn-220 and Rn-219; however, more comprehensive analyses are still required.

This review also indicates that there are factors that can decrease the indoor fractional equilibrium factor for Rn-222 and overall concentrations of each isotope of interest. The greatest contributor to reducing Rn-222 F_{eq} is air exchange during hours of peak activity, with an F_{eq} that can be as low as 0.27, a 32.5% decrease. As seen in Table 3, this value is similar for reduced HVAC use and open windows, decreasing the F_{eq} by 17.5 percent. This study shows another reducing factor, in which dwellings experience less radon and progeny concentrations during snowy conditions, decreasing the F_{eq} and overall risk. Further analysis shows that the indoor F_{eq} decreases by 4 percent based on 3-5 inches of snow, as it provides a buffering layer for decreased emanation from the ground. Despite being underground, thermal spas reduce the F_{eq} by 25 percent and tourist mines and show caves by 2.5 percent. This coincides with results in less densely populated areas and at lower altitudes, where air is less contaminated but still particle-rich for deposition, where there is greater air exchange in construction due to more permeable materials, and where there is more likely to be surface deposition on things like furniture or other aerosols not contributing to bronchial dose. Deposition can decrease the indoor radon fractional equilibrium factor by up to 12.5 percent, with an average reduction of 2.5 percent. Again, more extensive research needs to occur to understand the impacts on Rn-220 and Rn-219; however, current trends in Rn-222 F_{eq} reduction can loosely be applied.

Currently, US EPA's RVISL calculator utilizes models that do not address the comparative effects of smoking versus non-smoking, according to the US EPA Radiogenic Cancer Risk Models and Projections for the U.S. Population from 2011 (US EPA, 2011). Based on the results compiled in this review, the impacts of smoking, both chronic and periodic usage, are largely impacting the bronchial dose and overall excess lifetime cancer risk based on the high concentrations of Rn-222 present and the corresponding indoor fractional equilibrium factor of 0.72. A modification to the RVISL calculator to improve the safety of current users and the general public should be considered. Additionally, utilizing AQI data from a representative sample of cities could be used to improve the calculator in relation to smog. The RVISL calculator can be further modified once a greater understanding of impact factors has been established.

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