UNITED STATES AIR
FORCE SCHOOL OF
AEROSPACE MEDICINE

Detailed Information and Frequently Asked Questions for Bioenvironmental Engineers and Medical Providers on Occupational Exposure to Radon in Breathing Air

United States Air Force School of Aerospace Medicine
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14. ABSTRACT

Radon is a naturally occurring gas that is odorless, colorless, and chemically inert. It is present in naturally high levels in all 50 states and in certain areas around the globe. As a radioactive gas, radon has been associated with adverse health effects such as lung cancer in humans, who can encounter high levels of radon in their homes and at work. This document intends to aid the bioenvironmental engineers and medical providers of the Air Force in answering several common and uncommon questions that the public may have regarding this element.

15. SUBJECT TERMS

Radon, risk communication, occupational exposure, lung cancer, risk

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1.0 Sources of Information

The information used for answering the Frequently Asked Questions (FAQs) on radon in this document are based on two main sources:

1) Readily available materials and references from various Federal Agencies such the U.S. Environmental Protection Agency (EPA), the National Institute of Environmental Health Sciences (NIEHS), the National Toxicology Program (NTP), the Agency for Toxic Substances and Disease Registry (ATSDR), the Centers for Disease Control and Prevention (CDC), the International Agency for Research on Cancer (IARC), and the American Cancer Society.
2) Guidance and technical correspondence with the Department of the Navy (DON), Department of the Air Force (DAF), Air Force Civil Engineer Center (AFCEC), and Air Force Medical Support Agency (AFMSA).

2.0 Background

2.1 What is radon?

Radon is a naturally occurring gas that is odorless, colorless, and chemically inert. High levels of radon have been found in all 50 states. The most biologically important radionuclide of radon is radon 222 (^{222}Rn), a decay product in the series uranium 238 → thorium 234 → protactinium 234 → uranium 234 → thorium 230 → radium 226 → radon 222 → radon progeny (lighter elements). In the process of decaying to the next lighter element, radon emits an alpha particle represented by He^{2+} (the charged nucleus of a helium atom, containing two protons and two neutrons) and is thereby an emitter of ionizing radiation (that is, radioactive). Radon progeny emit alpha and beta particles and gamma rays and must be included in risk assessments.

Although radon 222 has a brief half-life of only 3.8 days, its long-lived decay predecessors, found in most ores and ground soils, are continually generating radon, particularly in regions with soils containing granite or aluminous shale, which have a higher concentration of uranium. Radon is a large contributor to an individual's background radiation dose, and is the most variable from location to location, with an average outdoor air concentration of 0.4 pCi/L in the US. All known isotopes of radon are radioactive, but radon 222 is the most stable.
Radon produced near buildings can penetrate foundations, and as a very dense gas accumulates in basements, crawl spaces, and attics that are poorly ventilated. The average US home air concentration is 1.3 pCi/L, but one in 15 homes has levels above 4 pCi/L, the level that EPA recommends homeowners not exceed. See Section 3.1 for a discussion of radiation units and dose units.

Radon in surface water is negligible, but radon in ground water, such as private wells, can contain significant levels, again, depending on local geology. Should this groundwater be used in water faucets or showers, it may be expected as a rule of thumb to off-gas about 0.1% of its dissolved radon gas concentration.

2.2 Why is this a concern for the Air Force?

Some epidemiological studies have shown a clear link between breathing high concentrations of radon and incidence of lung cancer. Most inhaled radon is rapidly exhaled, but the inhaled decay products readily deposit in the lung, where they irradiate sensitive cells in the airways, thereby enhancing the risk of lung cancer. The IARC lists radon as carcinogenic to humans, and the NTP lists radon as a known carcinogen. While radon is the second most frequent cause of lung cancer, after cigarette smoking, it is the number one cause among non-smokers with 2900 annual cases, according to EPA estimates.[1]

2.3 What is the Air Force doing to assess potential risk to its personnel?

The Air Force is committed to the safety and well-being of its personnel, and has established dose and contamination limits for practices by both military personnel and DAF civilians who work on base. Section 3.2 presents those safety levels in terms of radiation health effect units.

3.0 Regulatory Framework

3.1 What are the units of ionizing radiation in simple terms?

Ionizing radiation (energy sufficient to chemically alter vital cellular components) is not just an invisible hazard. The risks associated with ionizing radiation exposure include the type of radiation (alpha particle, beta particle, neutron, gamma ray, x-ray, and high energy ultraviolet light), the energy involved, and exposure scenario. The International System of Units (SI) uses the becquerel as the unit of **radioactivity**, defined as one nucleus decay per second (s^{-1}). Radon concentration in the atmosphere is usually measured in becquerel per cubic meter (Bq/m^3). Another unit of measurement common in the US is picocuries per liter (pCi/L). These two units are converted by 1 pCi/L = 37 Bq/m^3. Typical domestic concentrations of radon are approximately 100 Bq/m^3 (2.7 pCi/L) indoors, a little less than the 4 pCi/L EPA recommended action level. So that's how *radioactivity* is measured.

However, what we really care about in protecting people is the effective dose to human body tissue. Radiation **dose** is measured in terms of four factors: radioactivity exposure level and duration, the energy of the particular ionizing particles, whether the radiation remained external or was ingested or inhaled, and how it interacts with living tissues. For most sources of radiation (*but not for radon*), the sievert (Sv) ties all this together as a measure of the **health effect** of low levels of ionizing radiation on the human body. The sievert is of importance in dosimetry and radiation protection because it integrates exposure over a one-year period, similar to a time-weighted average. The rem (roentgen equivalent man) is an older, non-SI unit of measurement. A dose of 1 Sv = 100 rem; a dose of 1 mSv = 0.1 rem. This works for all but radon.

How is radon radioactivity connected to health effect? The only known health risks from radon are the development of lung cancer, and at a much lower incidence, some kidney diseases.

[1] https://www.epa.gov/radon/health-risk-radon

Radon exposures are generally indicated by the working-level (WL)[2], a unit originally developed to describe exposures of uranium miners to radon. Like the Sievert, the WL is time-weighted to measure average exposures. When an individual receives a dose of one WL in 170 hours (a miner's full-time month), the exposure then becomes called a "working level month" or WLM. Radon at 0.02 WL for 170 hr/month is approximately equal to 4 pCi/L or 148 Bq/m^3 of radon for 170 hr/month. If a residence contained radon at 4 pCi/L (the EPA action level) and its occupants were non-smokers but were exposed to radon continuously at that level over a lifetime, there is a chance of 7.3 additional lung cancer cases per 1000 people.[3] Risk to smokers are five to eight times higher than for non-smokers. So that's how *dose* or *health effect* is measured.

3.2 What are the Air Force standards for ionizing radiation?

On 20 November 2014, the Secretary of the Air Force ordered Air Force Instruction 48-148 "Ionizing Radiation Protection" to supersede AFI48-148, 21 September 2011. AFI 48-148, 20 November 2014 "specifies the requirements for the protection of AF personnel and their dependents as well as the public from exposure to ionizing radiation resulting from AF activities." AFI 48-148, 20 November 2014 includes Table A6-1, "Remedial Action Levels from Natural Sources of Radiation" that establishes radon exposure standards separate from all others, and is reproduced here:

Table A6.1. Remedial Action Levels from Natural Sources of Radiation.

Exposure to Radon	> 4 pCi/L average radon concentration

This is identical to the action level recommended by EPA. For more information on AFI 48-148, refer to http://static.e-publishing.af.mil/production/1/af_sg/publication/afi48-148/afi48-148.pdf

3.3 What is the EPA action level for radon?

In June 2003, the EPA published report EPA 402-R-03-003[4], "EPA Assessment of Risks from Radon in Homes" that summarized an extensive analysis of multiple epidemiological studies between radon exposure and incidence of lung cancer. Risk levels were developed by gender for both "ever smokers" and "never smokers" in terms of probability of disease per unit radioactivity concentration inhaled. The results predicted that for a lifetime (about 75 years) of breathing radon at **4 pCi/L**, the chance of developing lung cancer due to radon inhalation were 2.3% for the entire population, 4.1% for ever smokers, and 0.73% (7.3 per 1000) for never smokers. This was deemed an acceptable, conservative risk level. EPA does not have a drinking water limit for radon.

3.4 What is the OSHA PEL for radon?

The Occupational Safety and Health Administration (OSHA) is the federal agency responsible for the safety of American workers. In 1971, OSHA pointed to the Nuclear

[2] One WL is defined as that concentration of radon daughters in air that has a potential alpha energy release of 1.3×10^5 MeV in a liter of air, equivalent to 2×10^{-5} Joule per cubic meter of air (J/m^3).

[3] https://www.epa.gov/sites/production/files/2015-05/documents/402-r-03-003.pdf

[4] https://www.epa.gov/sites/production/files/2015-05/documents/402-r-03-003.pdf

Regulatory Commission (NRC) regulations of 1969 in 10 CFR 20, and set a permissible exposure limit (PEL) of 100 pCi/L to which a worker over 18 years of age can be exposed in 40 hours in a consecutive 7-day period. In 1979, NRC updated the regulated concentration from 100 pCi/L to 30 pCi/L, but for OSHA only the former limit remains legally enforceable. The only workers not covered by this OSHA PEL are miners, construction workers covered under 29 CFR 1926, and state and local workers in the 26 states, Pennsylvania for example, that have not entered into an agreement with OSHA to enforce their regulations.

4.0 Exposure and Exposure-Reduction Questions

4.1 What populations are most sensitive to ionizing radiation?

The only data for lung cancer from radon among children is a study among Chinese tin miners who were typically initially exposed before age 15.[5] The excess relative risk from inhaled radon per unit radioactivity was estimated for young miners to be at least twice that among the greater population. Application of that enhanced risk to children across the general population is controversial, however.

Epidemiological studies on populations exposed to radiation, such as atomic bomb survivors or radiotherapy patients, showed a significant increase of cancer risk at doses above 100 mSv (equivalent to twice the exposure that a uranium miner would be permitted to receive in one year). More recently, some epidemiological studies in individuals who received medical exposures during childhood (pediatric computed tomography scans) suggest that cancer risk might increase even at lower doses (between 50-100 mSv). So again, radiation may pose enhanced risk for children. This may be because children are growing, meaning their body cells are more actively dividing, and dividing cells are more sensitive to ionizing radiation. Also, children are more active and respire more than adults, which increases their relative dose. Many epidemiological studies show a positive association between radon exposure and childhood leukemia; however, most case control studies have produced a weak correlation, and the topic remains controversial.

4.2 How does radon behave in the body?

Actually, because radon is a noble gas, it does not chemically react with any other material, including body tissues, and is exhaled nearly completely (90%) within 100 minutes and more fully (99%) within 10 hours. However, radon progeny, formed by loss of He2+, are anions, and some of these readily attach to aerosolized room dust. Ironically, however, dust-attached radon progeny anions have only a 3% chance of striking and attaching to lung tissue, whereas the anions remaining unattached has a 50% chance.6 Once inhaled, radon progeny preferentially attach to the respiratory epithelium, particularly the bronchi, which is the site of most lung cancers. Further radioactive decay within the lung ensues, with emissions of alpha, beta, and associated gamma radiation that can damage vital biomolecules through either free

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[5] Xuan, XZ, JH Lubin, JY Li and WJ Blot (1993) A cohort study in southern China of workers exposed to radon and radon decay products. Health Phys. 64, 120-131.

[6] http://www.forensic-applications.com/radon/radon.html#EPA Guidelines And Regulations

radical interactions or DNA strand breaks or sequence alterations. Unrepaired DNA can lead to cancerous cells.

4.3 How are people exposed to radon?

The primary route of exposure to radon and its progeny is inhalation. Radiation exposure from radon is indirect. Actually, the health hazard from radon does not come primarily from radon itself, but rather from the radioactive products (progeny) formed in the decay of radon. Radon tends to accumulate within buildings in poorly ventilated areas, such as basements, crawl spaces, and attics.

4.4 How likely is radon to cause cancer?

Some researchers have estimated that the dose-response relation seems to be linear without evidence of a threshold, meaning that the lung cancer risk increases proportionally with increasing radon exposure. The EPA has published[7] separate tables for non-smokers and smokers to demonstrate the additive effect of smoking on lung cancer effects of radon. The tables are combined here:

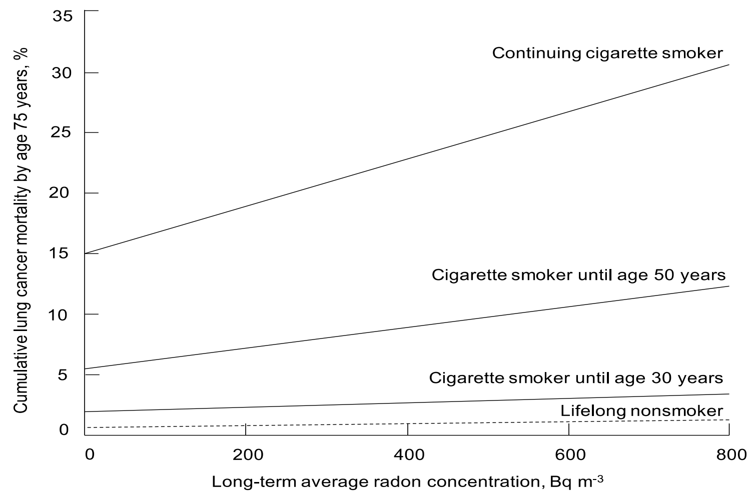
Risks Associated with Residential Radon Exposure

Radon Level	If 1,000 people who never smoked were exposed to this level over a lifetime, the expected number of lung cancer cases would be roughly	The risk of cancer from radon exposure compares to...	If 1,000 people who smoked were exposed to this level over a lifetime, the expected number of lung cancer cases would be roughly	The risk of cancer from radon exposure compares to...
20 pCi/L	36	35 times the risk of drowning	260	250 times the risk of drowning
10 pCi/L	18	20 times the risk of dying in a home fire	150	200 times the risk of dying in a home fire
8 pCi/L	15	4 times the risk of dying in a fall	120	30 times the risk of dying in a fall
4 pCi/L	7	The risk of dying in a car crash	62	5 times the risk of dying in a car crash
2 pCi/L	4	The risk of dying from poison	32	6 times the risk of dying from poison
1.3 pCi/L	2	(Average indoor radon level)	20	(Average indoor radon level)
0.4 pCi/L			3	

Thus, even at 2 pCi/L of radon breathed in a residential setting over a lifetime (half the EPA action level), four cases of lung cancer would be expected among 1000 non-smokers, and 32 among 1000 smokers. Another way to understand this is shown in the following graph from a British study[8]:

[7] https://www.epa.gov/sites/production/files/2016-12/documents/2016_a_citizens_guide_to_radon.pdf
[8] https://www.atsdr.cdc.gov/ToxProfiles/tp145.pdf

Figure 3-1. Cumulative Absolute Risk of Death from Lung Cancer by Age 75 Years Versus Long-Term Average Radon Concentration at Home for Continuing Smokers, Ex-Smokers, and Lifelong Nonsmokers in the United Kingdom



Source: adapted from HPA 2009

Even at very high long-term radon exposures, such as 800 Bq/m3 (21.6 pCi/L), a British non-smoker has about 35 chances in 1000 (3.5%) of dying from lung cancer, and continuous smokers have a 31% chance. Smokers who stop smoking early considerably reduce their odds of lung cancer mortality.

An interesting Japanese paper reported on a case-control study in which residential radon levels in the hot springs city of Misawa were compared with rates of death from lung cancer, and surprisingly, the mean contamination level was only 1.3 pCi/L, practically identical to the US average, and the radiation appeared insufficient to produce enough cases to establish a significant correlation.[9] In a Japan nationwide survey, the geometric mean level detected indoor was only 0.29 pCi/L, and only 0.1% exceeded 2.70 pCi/L.[10]

4.5 Is radon in food or drinking water?

As a gas, radon permeates everything not sealed. Ingested radon can, in rare cases, cause damage to the cells lining the gastrointestinal tract in a manner similar to the lungs, and it may also be absorbed into the blood. However, the National Academy of Sciences indicated that the primary cancer risk due to radon in drinking water arises from its transfer into indoor air and not from the ingestion of the water. Following ingestion of radon dissolved in water, the biological half-life for removal of radon from the body ranges from 30 to 70 minutes.

[9] Sobue T, Lee VS, Ye W, Tanooka H, Mifune M, Suyama A, Koga T, Morishima H, Kondo S (2000) Residential radon exposure and lung cancer risk in Misasa, Japan: a case-control study. J Radiat Res. 41(2):81-92.

[10] Suzuki G1, Yamaguchi I, Ogata H, Sugiyama H, Yonehara H, Kasagi F, Fujiwara S, Tatsukawa Y, Mori I, Kimura S (2010) A nation-wide survey on indoor radon from 2007 to 2010 in Japan. J Radiat Res. 51(6):683-689.

4.6 Are there methods to show whether people have been exposed to radon?

Radon in human tissues is not detectable by routine medical testing. Some radon progeny can be detected in urine and in lung and bone tissue. Various special methods are available for testing whether people have been exposed to radon. Biomonitoring involves estimating how much radon is present in the human body based on alpha decay from its longer-lived progeny, specifically polonium 209 and polonium 210. Levels of radioactivity of concern in the body suggest that some level of exposure occurred, but biomonitoring cannot determine when an exposure(s) caused the radon to be present. Moreover, the presence of radon in the blood or other body tissue does not automatically mean that harmful health effects will occur. Besides directly detecting radiation in the form of alpha decay emissions, other biomonitoring methods, such as analysis of blood for micronucleated red blood cells, may provide evidence of radiation damage.[11]

4.7 Should people concerned about exposures to radon get themselves tested?

Since among the general population biomonitoring can neither point to a specific source of radon exposure, nor offer information on whether levels received will definitely produce lung cancer, actions should emphasize measuring and remediating hazardous exposure levels.

4.8 How do I eliminate radon from my body if I have been exposed?

Currently, there are no medical interventions that will remove radon from the body. Radon and its progeny are naturally removed from the body via the urine.

4.9 Is there treatment for people who have been exposed to radon?

ATSDR does not recommend any specific treatments for people who have been exposed to radon.[12]

4.10 What can people do to reduce their risk of exposure to radon?

If radon concentrations are below 2 pCi/L, the EPA doesn't recommend mitigation due to the difficulty of reducing radon concentrations below that level. However, should mitigation be warranted, indoor radon levels can be reduced by the installation of a sub-slab suction (depressurization) system, also known as an active soil depressurization system (ASD). A radon vent fan connected to the suction pipe(s) draws the radon gas from below the structure and releases it into the outdoor air, while simultaneously creating a negative pressure (vacuum) beneath the slab. Sealing of openings to the soil can improve the operation and efficiency of the ASD system. Certified radon mitigation experts can be found by contacting local state health or environmental program. Measures to prevent high radon levels in new construction are expected to be effective at reducing radon-related lung cancer deaths.

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[11] Linhares D, Garcia P, Rodrigues A (2017). Radon Exposure and Human Health: What Happens in Volcanic Environments?, Radon, Prof. Feriz Adrovic (Ed.), InTech, DOI: 10.5772/intechopen.71073. Available from: https://www.intechopen.com/books/radon/radon-exposure-and-human-health-what-happens-in-volcanic-environments-

[12] https://www.atsdr.cdc.gov/ToxProfiles/tp.asp?id=407&tid=71

In addition to this, cessation of smoking when also exposed to radon can significantly reduce the chances of developing lung cancer.

4.11 My workplace breathing air exceeds the EPA radon action level; will I get sick?

The evidence for a causative relationship between cumulative radon exposure and lung cancer comes from epidemiological studies among miners and among survivors of atomic bomb explosions in Nagasaki and Hiroshima, Japan. Radiation sickness is real. Also, there has been limited research in which rats exposed to radon developed lung cancer, and the results are fairly predictable.[13,14] Therefore, depending on the contamination level and how long you have breathed it, there could be an increased statistical risk of eventually getting sick, but it largely depends also on whether you smoke, how long you have smoked, and possibly your genetic makeup. As shown in the plot above, even 22 pCi/L breathed over a lifetime by a non-smoker carries less than a 5% risk.

5.0 Pregnancy and Children

5.1 If I am pregnant, is it safe to breathe air at work?

The reported dose of radiation to result in an increased incidence of birth defects or miscarriage is above 200 mSv, or 20 rem (equivalent to a year working full-time in a mine at 120 pCi/L). The association between high doses of ionizing radiation and fetal developmental problems is well established, but one survey of Norwegian pregnancies during the first three years after the Chernobyl accident in April 1986 showed there was scant evidence that low-dose fallout (the mean in Norway was 0.3 mSv over the first year) increased the risk for serious fetal neurodevelopmental problems. Most X-rays are safe to get during pregnancy, as most diagnostic procedures are less than 50 mSv, or 5 rem (equivalent to a year working full-time in a mine at 30 pCi/L).

5.2 Is it safe to breastfeed?

The well-established benefits of breastfeeding are expected to far outweigh any deleterious effects related to the transfer of radon from mother to child via breastmilk. Concerns about radon exposure and breastfeeding should be discussed with a child's pediatrician or other healthcare provider.

5.3 What are the potential health effects of radon exposure in children?

The physical composition of children leads to faster rates of exposure through inhalation, given that their respiratory rate is higher than that of adults, resulting in more gas exchange and

[13] Lafuma J, Chmelevsky D, Chameaud J, Morin M, Masse R, Kellerer AM (1989) Lung carcinomas in Sprague-Dawley rats after exposure to low doses of radon daughters, fission neutrons, or gamma rays. Radiat Res. 118(2):230-245.

[14] Bijwaard H, Brugmans MJ, Leenhouts HP (2001) A consistent two-mutation model of lung cancer for different data sets of radon-exposed rats. Radiat Environ Biophys. 40(4):269-277.

more potential opportunities for radon to be inhaled. Also, child lungs are smaller, so that relative to an adult there can be amplified effects, predominantly including lung cancer and respiratory illnesses such as asthma, bronchitis, and pneumonia. While there have been numerous studies assessing the link between radon exposure and childhood leukemia, the results are largely varied. Genotoxicity has been noted in children exposed to high levels of radon, specifically a significant increase of frequency of aberrant cells was noted, as well as an "increase in the frequencies of single and double fragments, chromosome interchanges, [and] number of aberrations chromatid and chromosome type".[15] As noted earlier, the enhanced risk to children for developing lung cancer from radon is controversial at this time.

6.0 Additional Information for Medical Providers Regarding Health Effects Observed in Humans and Laboratory Animals Exposed to Radon

The Agency for Toxic Substances and Disease Registry has published (May, 2012) a 283-page treatise, "Toxicological Profile for Radon" available online at https://www.atsdr.cdc.gov/toxprofiles/tp145.pdf. It contains an exhaustive review of the problem radon poses for our population. The radioactivity decay charts and glossary alone are worth reviewing for gaining clarity on this complicated public health issue.

[15] Druzhinin VG, Sinitsky MY, Larionov AV, Volobaev VP, Minina VI, Golovina TA (2015) Assessing the level of chromosome aberrations in peripheral blood lymphocytes in long-term resident children under conditions of high exposure to radon and its decay products. Mutagenesis. 30(5):677-83.