Radon: Not so Noble

Radon in the Environment and Associated Health Problems

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Radon is a radioactive noble gas that occurs naturally but becomes an environmental hazard when it remains concentrated in enclosed places such as houses, caves and mines. Rocks and soils containing uranium produce radon during radioactive decay process. Being a gas, radon diffuses through soils and rocks and enters the atmosphere. Radon is water soluble and may contaminate drinking water supplies. Uranium miners and residents of houses built on uranium bearing rocks or soils are exposed to high concentrations of radon. Continuous exposure to radon causes lung cancer in human beings.

Chemistry of Radon

Radon is widely dispersed in the environment. It is highly radioactive and decays by the emission of energetic α particles. Radon is the heaviest of the noble or chemically inert gases. Its chemical inertness is due to its stable electronic configuration [$5s^2 5p^6 5d^{10} 6s^2 6p^6$]. The natural radioactive series beginning with ^{238}U is the major source of natural radiation in the environment. Each ^{238}U nucleus emits an α particle, and thereby an atom of the thorium isotope (^{234}Th) is formed. In the sequence of reactions, ^{206}Pb is formed, which is non-radioactive (stable) and therefore stops the sequence. Of particular interest is the portion of the 14-step sequence of ^{238}U radioactive decay series, which involves the formation of gaseous radon, which is mobile. Radon isotope 222 has a half-life of 3.8 days, long enough to diffuse into the atmosphere through the solid rock or soil in which it is formed. Radon is found in natural sources only because of its continuous replenishment from the radioactive decay of longer lived precursors in minerals containing uranium or thorium. More than 25 isotopes of radon have been identi-

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fied. Three of these, ^{222}Rn (radon), ^{220}Rn (thoron) and ^{219}Rn (actinon) occur in nature as members of the uranium, thorium and actinium series, respectively (*Figure* 1). The rocks of the earth's crust contain approximately 3 ppm of ^{238}U (the long lived head of uranium series) 11 ppm of ^{232}Th (the head of the thorium series) but only 0.02 ppm of ^{235}U (the long lived member of the actinium series). The actinium series is of minor importance both because of the relatively low abundance of ^{235}U and because of the short half-life (4 sec) of ^{219}Rn, the noble gas member of the series.

Any surface exposed to ^{222} Rn becomes coated with an active deposit which consists of a group of short-lived daughter products, including ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po and ^{210} Pb. The radiations of this active deposit are energetic α particles, β particles and γ rays. Particularly noteworthy are the penetrating gamma radiation of ^{214}Bi, which are of practical use in radiotherapy, radiography and other purposes. Thoron and actinon also lay down an active deposit on surfaces exposed to them, but they and their decay products have not had the same general interest and concern because of their shorter lifetimes.

Distribution in the Environment

Soil: Soils and rocks rich in uranium are the main sources of radon to which people are exposed. Soil radon activity under natural environmental conditions is influenced by soil moisture content, barometric pressure variations and temperature and structure of soil. Loose sandy soil allows the maximum diffusion of radon gas, whereas frozen, compacted or clay soil inhibits its flow. Elevated radon values tend to occur over the fracture zones in soil, which aids convective transport of the soil gas into the environment and lowers its concentration in the soil. Higher radon concentration in soils during winter is attributed to capping by frozen soil layers. Similarly, higher radon concentration in wet soils is attributed to capping by water layers. Wind speed effects on subsurface radon activities have not been observed while barometric pressure changes can

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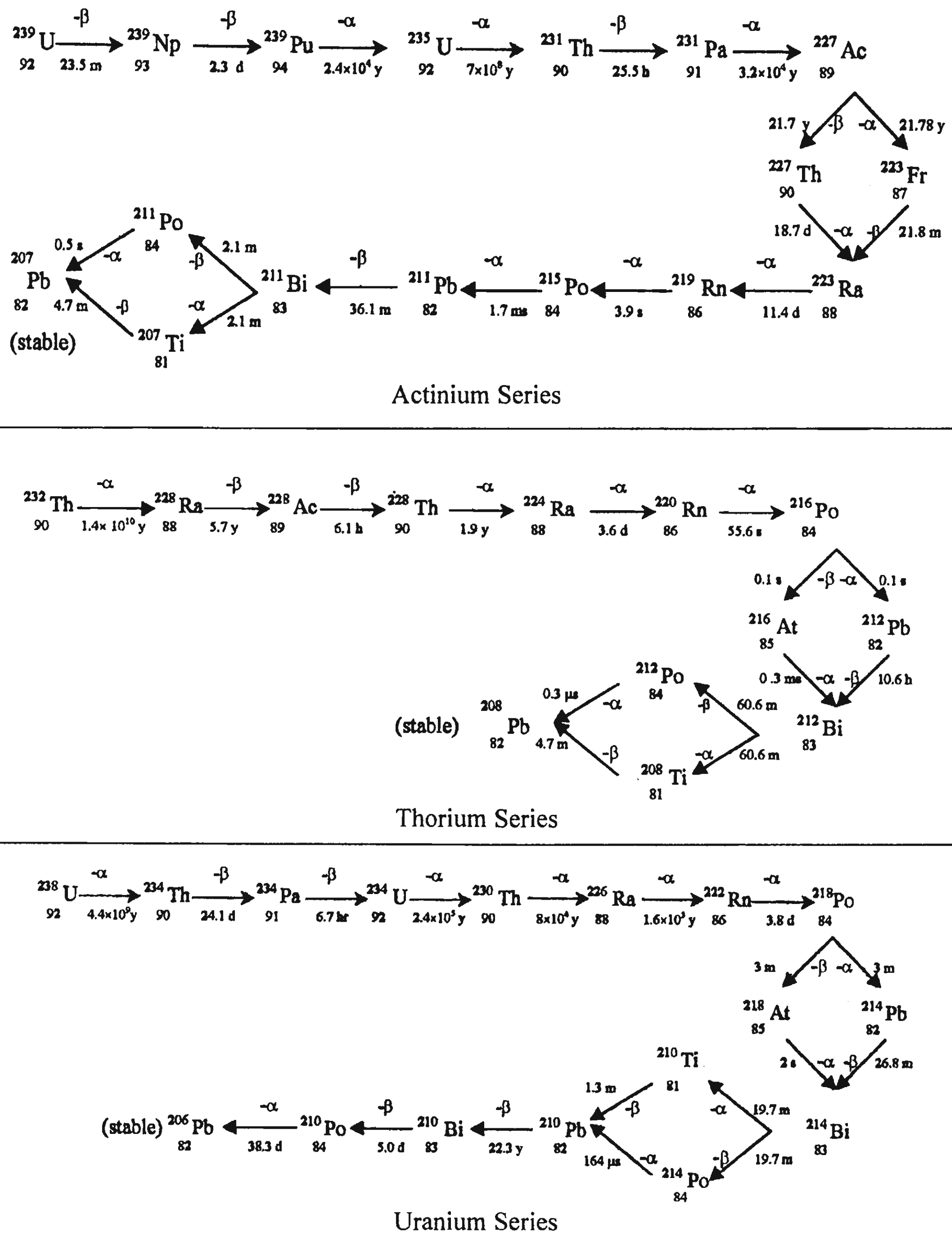

Figure 1. Existence of radon isotopes in nature as members of actinium, thorium and uranium series.

significantly affect the exchange of soil radon with the atmosphere.

Water: Radon is readily soluble in water. Since ground and surface water are in close contact with soil and rocks containing small quantities of radium, it is not surprising to find radon in public water supplies. Rivers carry dissolved ^{226}Ra (1600 yrs.) to the oceans where radioactive equilibrium between ^{226}Ra and ^{222}Rn is achieved. A deficiency of ^{222}Rn exists in water near air sea interface and an excess exists near the ocean floor. ^{222}Rn atoms cannot escape readily from the water surface with the result that maritime air masses contain only about 1% as much ^{222}Rn as air over the continents. Surface and groundwater samples collected from areas near uranium deposits show high levels of radon. Wells and springs with high radon activities appear to be associated with the production of water from the horizons of unusually high hydraulic conductivity wherefrom dissolved soil radon in water easily enters the wells and springs.

Atmosphere: When radon (^{222}Rn or ^{220}Rn) diffuses from soil to air, it is mixed throughout the lower atmosphere by eddy diffusion and the prevailing winds. Typical concentrations of ^{222}Rn just above the ground may be exceeded by a factor of 10 or more when radon, like atmospheric pollutants are trapped by temperature inversions at or near earth's surface. Mean radon levels are found to be higher during those times of the year when atmospheric stability is the greatest. The decay products of radon, both short and long-lived are positively charged heavy metal ions, which soon attach themselves to airborne particulate matter. From the atmosphere, they may be removed by decay, gravitational settling and action of rain or ion migration under the influence of natural atmospheric electric fields. Radon and its daughters play an important role in atmospheric electricity. Near the earth's surface, almost half of the ionization of the air is due to ^{220}Rn and ^{222}Rn and their daughter products.

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Plants: It has been shown that most of the ^{222}Rn released

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originates in the plant growth medium, rather than decay from ^{226}Ra within the plants. Plants take up radon from the soil environment if grown on soils producing radon. It is suggested that ^{222}Rn is taken up by mass flow but at the leaf mesophyll, it diffuses independent of water. Experiments have shown that ^{222}Rn released by the plants in a controlled environment chamber may be unrelated to the quantity of water transpired. LAI (leaf area index) rather than plant species is proposed as a major factor controlling the quantity of ^{222}Rn released from plants.

Others: Various types of construction materials e.g. bricks, cement, sand, gravels, concretes have been identified as sources of radon. The diffusion of ^{222}Rn from building materials is influenced by moisture content of the material, density, the presence of sealants, the material itself and the nature of the substances with which it is mixed. Both emanation rates and fractional escape are functions of material thickness.

Fly ash is also a source of radon in the environment, as it may contain high concentrations of uranium and its decay products. The radon exhalation rate from fly ash, when measured spectrometrically was found to be more than a typical soil, having higher concentration of uranium and its decay products, especially ^{226}Ra.

Phosphogypsum is a by-product of phosphate fertilizer production process. The phosphate ore used in these chemical processes contains the naturally occurring radioactive material uranium and all its subsequent decay products including radon. During processing, uranium generally remains in phosphoric acid products, while the daughter, ^{226}Ra tends to be concentrated in the phosphogypsum. Phosphogypsum has physical properties that make it useful as a sub-base for roadways, parking lots and similar constructions.

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Indoor Radon

Most radon that seeps into homes comes from the top few meters of the soil below and around the foundation; radon produced much deeper than this will probably decay to a nongaseous and therefore immobile form, before it reaches the surface. Radon enters the basements of homes through holes or cracks in their concrete foundations. The intake is increased significantly if air pressure in the basement is low. The material used to construct homes and water from artesian wells are often potential sources of radon in homes. When well water is heated and exposed to air, radon is released to air. Dissolved radon may also be released from water coming out of showerheads in bathrooms. The home heating systems also have a role to play in regulating indoor radon concentrations. Furnaces, while operating within homes, develop a partial vacuum inside, drawing more radon-poor outside air than radon-enriched soil air. Consequently, indoor radon may be much less in these dwellings than homes with electrical heating systems. The source potential of soil depends on two parameters: The release rate of radon into the soil pores and the volume of soil that can contribute radon to indoor air. Radon enters buildings as a component of soil gas drawn from the soil by mass flow, driven by the pressure difference between the house and the soil beneath. The emanation of radon gas through the ground in areas with an igneous or metamorphic basement increases with the fracturing of the underlying rock, and also with its water content. With the tendency for the gas to concentrate in buildings where air exchange is limited, radon is becoming a major component of indoor air pollution. Soils with higher aeroradioactivity tend to have homes with higher indoor radon. USEPA (United States Environment Protection Agency) has fixed an action level of 4 pCi/L for radon in houses. In a study carried out in dwellings of Doon Valley, NW India, the indoor radon values were found to be influenced by the geology of the area, building materials and on the construction of the houses. Wind direction and speed are two important factors, which control entry of radon into houses

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after its emanation from the soil around. High radon concentrations in the village of Umhausen, Austrian Tyrol, which constituted a significant health hazard in the indoor environment were attributed to the giant landslide of Koefels nearby. The landslide of Langtang Himal, Nepal also resulted in high radon emanation from soil. In both the cases, although the uranium and radium contents of the rocks was low, their fractured and crushed nature resulted in the production of high surface area and circulation pathways which helped pathways for convective transport of radon.

Health Effects

Radon is chemically inert in ambient conditions and remains as a monatomic gas. As such, it becomes a part of the air that we breathe once it enters our homes. Because of its inertness, physical state, and low solubility in the body fluid, radon itself does not pose much of a danger to human beings, since the chance that it will disintegrate during the short time it is present in our lungs is small, and the range of alpha particles in air before they lose most of their energy is less than 10cm. The danger arises from the radioactivity arising from the three elements produced in sequence by the disintegration of radon, namely polonium, lead and bismuth. In macroscopic amounts these elements are solid, and when formed in air from radon they all quickly adhere to dust particles. When radon and thoron decay, their daughter products tend to attach themselves to the ever-present inert dusts in the atmosphere. Adsorbed radioactive daughters thus have the effect of endowing the non-radioactive dust of the atmosphere with apparent radioactivity. Studies on the particle size spectrum of the dust on which the radon daughters are adsorbed revealed that radioactivity is associated with dust particles in the range 0.084-0.2 micron. Some dust particles adhere to the lung surfaces when inhaled, and it is in these conditions that those elements pose a health threat. In particular, both the ^{218}Po which are formed directly from ^{222}Rn, and the ^{214}Po that are formed later in the sequence emit energetic α particles that can cause radiation damage to the bronchial cells located near the dust particles. This damage can eventually lead to lung cancer. Inhaled radon is the second leading cause of such cancers, smoking being the first.

The greatest exposure to α particles from radon disintegration is experienced by those miners who work in poorly ventilated underground uranium mines. The exposures reported for the mining studies are ordinarily two or three orders of magnitude higher than those expected for indoor settings. Their rate of lung cancer is indeed higher than that of the general public, even after excluding the effects of cigarette smoking. Based on the epidemiological studies of the miners, lung cancer is likely to be higher in males and females over 35 years of age. From statistical data relating their excess incidence of lung cancer to their cumulative level of exposure to radiation, a mathematical relationship between cancer incidence and radon exposure has been developed. Scientists have attempted to extrapolate this relationship in order to determine the risk to the general population from generally lower levels of radon to which the public is exposed. Based upon linear extrapolation, one recent estimate concluded that the increased chance of contracting lung cancer is 1 in 250 and therefore about 10,000 lung cancer deaths per year in the US are due to this cause. However this estimate may be too high, since the miners work in much dustier conditions than are found in homes and their breathing during hard labour is much deeper than normal; consequently, there is much more chance that radon daughters will find their way deep into the lungs of miners compared to those in the general population. The Walsh Healy Act of 1968 established a protection guide for ura-nium workers at four working level months (WLM) per year, where the working level (WL) is defined as any combination of radon daughters in 1 litre of air that will produce 1.3×105 MeV of alpha energy. This would be equivalent to a ^{222}Rn concentration of 100 pCi/l in equivalence with its short-lived alpha emitting progeny. WLM is a cumulative exposure to a ^{222}Rn concentration of one WL for 170 working hours in one month. Four WLM per year is consistent with a ^{222}Rn level of

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30 pCi/l, assuming equilibrium with the shorter lived daughters. The dose to the lung from ^{212}Pb (10.6 hr) and its daughters in the thorium series is not believed to add appreciably to that received from the ^{222}Rn series. In addition to the problems created by radon for miners, uranium mines and tailing piles in some western states of the USA are the sources of additional radon in the atmosphere and unless precautions are taken, may add substantially to the radon concentration in the drinking water drawn from surface run-off or wells in nearby communities.

Mitigation of Health Hazards

• Sealing of cracks in the walls and basement of dwellings may be effective in reducing indoor radon concentration, as cracks are the major pathways of radon entry in homes. Sealing may be done with a gas membrane, made of cross-laminated polyethylene, placed between two layers of tar-paper, to protect it from damage. It should be ensured that the membrane is tightly fastened to the foundation walls with plywood strips and sealed with industrial grade urethane caulking. Where there is a possibility of the building materials having precursors of radon (e.g. coal and fly ash bricks), sealing is a necessity.

• Exhaust fans may be used in homes to drive radon out of the rooms where cross ventilation is poor or where windows are generally kept shut due to cold, especially in temperate countries. In tropical countries, windows should be kept open most of the time to allow cross ventilation.

• If technology is available at reasonable price, radon-monitoring instruments should be installed at homes having risks of developing high indoor radon concentrations. This will help dwellers to take necessary precautions.

• It is necessary to prepare national and regional radon potential maps, corresponding to cool, warm, wet and dry weather conditions, as the seasons influence radon levels. These maps can be immensely beneficial for identifying high radon areas, where appropriate precautions can be taken by inhabitants.

• In underground mines, where workers are exposed to high radon concentrations, artificial respirators must be provided to the workers to check radon entry into their bodies.

• Provision of ventilation in underground mines may significantly reduce the radon levels to safe levels inside a mine. Mine openings themselves are used for air movements in a ratio of weight of air transport to weight of mineral removed approaching to 10 or 20 to 1. Multiple number of exhaust fans may be installed for driving mine air outside. Development of high-speed electronic digital computers has made it easier to solve intricate problems associated with mine ventilation.

• Cigarette smokers should keep their exposure to radon as low as possible. Smokers have approximately eight times the risk of developing lung cancer from radon as non-smokers.

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Applications of Radon

• Exhalation of radon from ground depends on the fractures in rock strata and groundwater content. Detection of emanating radon has been found useful as an efficient backup of conventional methods (e.g. photo interpretation, electrical geophysics etc.) of prospecting underground aquifers.

• Pattern of radon emanation from soil has been used in the studies of permafrost distribution in Alaska. Radon contents in surface soils have been found to correspond well with frozen ground distribution.

• Ocular or periorbital squamous cell carcinoma in horses has been treated with ^{222}Rn interstitial implants. Follow-up studies in subsequent two years have shown a non-occurrence rate of the complication to the tune of 60-70%.

• Radon has been used in studying the relationship of groundwater with surface water flows. ^{222}Rn measurements were done and were used together with stream discharge data in a mass balance equation to quantify groundwater inputs.

Radon monitoring may help in the detection of uranium and associated minerals lying under the rocks in the earth's crust.

• Residence time and velocity of flowing water through soil can be measured, using radon as a tracer.

• Radon is used as a naturally occurring tracer in the studies of gas transport properties of soils.

• Radon (^{222}Rn) and thoron (^{220}Rn) are used as naturally occurring tracers for the measurements of turbulent transport in the atmosphere. Wind circulation and movements can be studied by continuous measurements of changes in vertical or horizontal distribution of the gas. Long lived radon isotopes have been used as tracers in the studies of motions of air mass systems from Sahara across the North Atlantic, from continental regions to the trade winds in Hawaii and from the continents to the Arctic in the Southern Hemisphere.

• Structural changes in a soil during and after logging operations can be studied by 'radon exhalation technique'.

• Radon monitoring may help in the detection of uranium and associated minerals lying under the rocks in the earth's crust. High emanation of radon from soil generally points to the possibility of finding deposits of uranium and other minerals in the area.

• Development of new cracks in the rock strata before the onset of an earthquake may result in increased radon movements in soil, which is picked up by moving groundwater. This results in slow buildup of radon in groundwater, well water and springs, which indicate the possibility of an earthquake in near future.

Conclusion

Health hazard from exposure to radon is not an acute problem, if considered globally. But a looming danger of health complications cannot be ignored due to the health risks involved in areas where radon concentration assumes dangerous proportions. The importance of the problem can be easily perceived from the fact that international scientific bodies like International Commission on Radiological Protection (ICRP) and United Nations Scientific Committee on the Effects of Atomic Radiations (UNSCEAR) are engaged in studying the exposure of radon to both occupational workers as well as members of the public. But in tropical countries like India, due to the climate and living conditions, houses are generally well ventilated and consequently indoor radon pollution has not reached alarming levels.

Acknowledgement

The author gratefully acknowledges the assistance and constructive criticism of Shalini Singh during the preparation of the manuscript.

Suggested Reading

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Art and science have this in common: they provide meaning and sense to human experience. But the sense of the meaning is thoroughly different. It has been observed that art transforms general experiences into a single and unique form, whereas science transforms detailed single experiences into a general form.

– Victor F Weisskopf