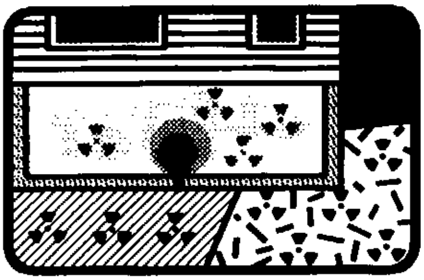

URBAN GEOLOGY 2.
Radon: Sources, Hazards and Control

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INTRODUCTION

Long-term exposure to elevated concentrations of radon gas increases the risk of lung cancer in humans. Radon can enter homes and other structures from the soils and rocks on which they are built, and with ground water used for domestic and industrial purposes.

Natural hazards have always been part of the world in which we live. Obvious hazards include extremes of temperature, floods, earthquakes and avalanches. Mankind has learned to adapt to these conditions through modification of behavior. Less obvious hazards (*e.g.*, bacteria, viruses, poisonous plants, heavy metals, arsenic and gases) may also pose a threat at some locations, from time to time. The human body is marvellously designed to handle natural risks, and certain thresholds must be surpassed before real danger exists. It is important to recognize the threshold concept, and deal with all hazards in a calm and rational way.

In this discussion, the radioactive gas radon is considered: its health effects, natural sources, detection and measurement, and how the gas can be controlled so that its potentially harmful influences on human health are minimized.

RADON

Radon is a naturally occurring radioactive gas. It is one of the daughter products of spontaneous disintegration of the most abundant isotope of uranium, ^{238}U. It is a transient element with a half-life of 91 hours, 48 minutes. (A half-life is defined as the time required for a given quantity of radioactive atoms to decay to one-half the original number).

Radon is a noble gas. It does not combine chemically with any other element and carries no electric charge. It is the immediate daughter of ^{226}Ra, and all of the gas is derived from the spontaneous disintegration of radium atoms. Radium is a daughter of uranium, but the two elements may behave differently in the same geologic environment, and can be separated one from the other by substantial distances. Radon is soluble in water and may travel long distances from its source in ground water and in surface drainages. It is more soluble in air than in water and will pass readily to the air, particularly if the water is agitated mechanically (Thompkins, 1982a, 1982b, 1982c; Atomic Energy Control Board of Canada, 1978).

SOURCES

Natural sources of radon are rocks, soils and, indirectly, water. Rocks and soils normally contain small quantities of uranium (1-10 parts per million). Some rocks are enriched in uranium to the extent that the metal can be recovered economically, for example, the pre-oxygenation Proterozoic conglomerates at Elliot Lake on the north shore of Lake Huron, and certain pegmatites near Bancroft in the highly metamorphosed late Precambrian Grenville Province rocks of eastern Ontario.

Sedimentary rocks that contain organic material are frequently moderately enriched in metals, including uranium. "Black shales" and bituminous limestones carry ten to several thousand parts per million (ppm) uranium, and may underlie hundreds of square kilometres. Black shales as radon sources have been studied extensively in Sweden (Akerblom and Wilson, 1982), but similar country-wide environmental studies have not been done in North America. Neither are there construction criteria in North America, such as are mandatory under the 1980 Swedish Building Code, to limit the annual average in new buildings to <1.89 pCi/L or <70 Bq/m^3 of air (Akerblom and Wilson, 1982). (Radon concentrations in the United States are measured in picoCuries per litre of air (pCi/L). A picoCurie is equivalent to 0.037 radioactive decays per second. In Canada, radon concentrations are measured in Becquerels per cubic metre of air: 800 Bq/m^3 = approximately 21 pCi/L; 1 Becquerel = 1 radioactive decay•s^{-1}.)

The upper part of the Collingwood Member of the Lindsay Formation (Middle Ordovician) is a bituminous calcareous shale/limestone unit that underlies much of the area north of Lake Ontario through to the Bruce Peninsula and Manitoulin Island. It crops out in the northern part of Metropolitan Toronto, in York Region, and in areas to the north and east. Work done by environmental surveyors during the past ten years confirms these rocks to be a significant radon source. Other "black shales" that may be radon sources in southwestern Ontario include the Marcellus Formation, which is exposed along the north shore of Lake Erie south of London, and the Kettle Point Formation, which sub-crops in much of the area between London and Sarnia. The Eastview Member of the Lindsay Formation near Ottawa has been investigated as a possible uranium source, and, although no economically mineable deposit has been found, is noted for an elevated uranium content. In the same area, the overlying Billings Formation black shales may also be metal rich locally.

The formation of coal is accompanied by extremely reducing conditions. Metal complexes, including uranium, are precipitated very effectively from surface waters flowing into the "coal swamps". It is, therefore, common to find strong general metal enrichment in shales that accompany coal beds and, if the ash content is high, within the coals themselves. For example, spoil heaps from coal mining in Cape Breton Island, Nova Scotia, have been found to give strong airborne radiometric signatures that are confirmed by gamma ray measurements on the ground.

Granites often carry 10-40 ppm uranium, and some may contain from several hundred grams to one or more kilograms of uranium per tonne.

Phosphate-bearing rocks are commonly uranium enriched (Cathcart, 1978). This author once evaluated a "uranium deposit" that turned out to be a collection of phosphate-rich coprolites (fossil dinosaur dung) in a meander of a Cretaceous-age stream. The "deposit" had been located by gamma ray spectrometry that measured the intensity of the characteristic energy of uranium which is released by decay of the immediate daughter of radon, ^{214}Bi.

Ground water may dissolve radium and transport it great distances where it can be redeposited and concentrated. The resulting "displaced" radon anomalies are sometimes strong enough to constitute a health hazard.

Radon that is dissolved in water is often brought indoors from wells and released in kitchens and bathrooms (Hess *et al.*, 1982; DOHE, Maine Department of Human Services, 1983). For example, 130 well water samples from the Ottawa area gave an average of 505 pCi/L radon, with a range of 10-6151 pCi/L. The average radon content of 900 samples from a 15,000 km^2 area in Saskatchewan gave a mean radon content of 355 pCi/L, with higher values being 1000 pCi/L. Seventeen hundred well water samples from a 25,000 km^2 area underlain by Carboniferous sediments in the Maritimes gave an average of 857 pCi/L, with maximum values of more than 2500 pCi/L (Dyck, 1979, 1980).

In Canada, glacial deposits of material derived from uranium-enriched source rocks may be transported long distances and spread widely in tills and outwash deposits.

There are no confirmed Canadian cases of indoor radon problems originating from uranium milling tailings such as happened at Grand Junction, Colorado in the 1950s.

Waste rock from coal mines is frequently used for fill and road-building material, however, and buildings situated on or adjacent to this kind of fill or over drainage from spoil heaps should be checked for radon accumulation.

Radon sources in any area can be identified by reference to the local bedrock and surficial geology, and confirmed by geochemical testing. In this regard, Canadian federal and provincial geological surveys have published results of extensive studies on the uranium and radon content of ground waters, including Prince Edward Island (Dyck, 1979, 1980). Airborne radiometric surveys cover much of the country. Regional geochemical surveys that include uranium give data that are very useful in outlining areas of potential radon gas risk.

It should be emphasized that there is also a wealth of environmental information in exploration geochemistry files, information which should not be overlooked simply because it has been collected for mineral exploration purposes. Mining-related landscape chemistry data can be invaluable in defining the natural chemical parameters of local and regional environments, and is readily available from the assessment records and the annual publications of federal and provincial ministries that deal with natural resources, energy and mines.

Federal and provincial ministries of agriculture also have soil chemistry studies that contain much useful data for environmental assessments and studies, although this author is not aware of a great deal that refers directly to radon or uranium. The R-2000 energy-efficient housing program of the early 1980s collected indoor radon data from new homes throughout Canada, and that information is available on request.

One should be constantly on the alert for other unexpected sources of valuable environmental data. For example, the federal Department of Health and Welfare carried out a study of naturally fluorine-bearing drinking water in the 1950s, prior to instituting fluoridation of municipal water supplies. The results of this work could be applied indirectly to radon risk evaluation in those areas where uranium was known to be related to fluorite-rich phases of granite intrusions. The data also proved invaluable in planning a country-wide fluorite exploration program. Some forestry studies have been useful in helping to define anomalous metal distributions in soils, and in tracing specific rock units beneath extensive overburden cover. Local health departments often have water chemistry information of historical significance and current relevance.

HEALTH HAZARDS

Radon gas is chemically inert. Although it decays with the release of an alpha particle (two protons and two neutrons, *i.e.*, a helium nucleus) and a gamma ray, the immediate daughters of radon (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) are responsible for the greater part of radon-associated medical problems. These radon daughters are chemically active and will attach themselves to particulate matter in the air; if inhaled, they may remain in the throat and lungs by adhesion to exposed tissue. As these daughters decay, they emit alpha particles, beta particles (electrons), and gamma rays (electromagnetic energy similar to light, but of much shorter wavelength).

Alpha emission is the most energetic of the decay sequence and is the prime cause of physical cell damage. Beta particle emission is less powerful, but also can be responsible for disruption within living cells. Natural gamma radiation through tissue is classed as a low linear energy transfer event and is not a significant direct mechanical contributor to cell damage. Gamma radiation damage to cells results largely from production of ions by the gamma rays, and subsequent interaction (often oxidation) of molecules within the cells. Alpha and beta emissions will also cause ionization in the cells, but much of the damage from particulate emissions is mechanical.

Due to the relatively short range of spontaneously emitted sub-atomic particles in tissue (usually <40 μm), the radiation dose from inhaled and adsorbed radon daughters will be concentrated near the surface of lung and throat tissue. The most critical effect of radon daughter-related particulate radiation exposure is damage to cell deoxyribonucleic acid (DNA). This damage can take many forms, including deletion of a base, chemical cross-linking of two DNA strands, and partial or complete breaks in the DNA chain. In the latter regard, DNA may suffer single strand breaks in the two-strand helix or the chain may be severed in one or more places. In most cases, the simple types of damage are repaired by enzymes in the cells (Upton, 1982). Lack of repair or misaligned repair of the DNA chain may result in reproduction of new cells with similar modified characteristics. Most of these new cells are likely to be controlled or eliminated by the body's defense systems, but some may prove uncontrollable and malignant.

Domestic radon exposure is estimated to be responsible for 10,000-15,000 excess lung cancer deaths per year in the United States and Canada, and currently is considered responsible for more deaths than any other environmental hazard. This suggests that there is one death per annum for approximately every 25,000 North Americans that can be attributed to radon exposure (Hamilton, 1991; Guimond, 1991; Marshall, 1990; Budnitz *et al.*, 1979; Hurwitz, 1991; Moeller, 1991; Cohen, 1991). In comparison, annual cigarette smoking-related deaths are estimated to be one per 1800 of population, and those related to all phases of the nuclear power industry (*e.g.*, uranium mining, milling, refining, transportation) are estimated to be one per 2.6 million (Upton, 1982). Some combinations of environmental risks appear to have cumulative effects. For example, studies have shown that the risk of lung cancer in uranium miners is increased by a factor of about ten for cigarette smokers, compared to non-smokers exposed to the same radon concentration. It appears reasonable to expect similar results from exposure to indoor radon.

Public perception of radiation risks is reflected by the attention given to radioactive waste, possible reactor accidents, nuclear weapons fall-out, diagnostic X-rays, and indoor radon. Cohen (1991) has calculated the cost per life saved by these expenditures to be US $200,000 for radon, $200,000,000 for radioactive waste, and $2 billion for reactor accidents. This is interesting, when one considers that radon accounts for 55% of the radiation health hazard experienced by North Americans. A further 16% comes from other natural sources (including cosmic radiation, rocks and soils) and 11% originates within the human body. X-rays and nuclear medicine account for 15% of the average annual dose, consumer products for ~3%, and <1% from occupational exposures, fall-out, the nuclear fuel cycle, and other miscellaneous sources (Marshall, 1990).

CONTROL

If, philosophically, no risk for an individual or for a society can be regarded as acceptable if it is easily and inexpensively avoided, then (excessive) indoor radon exposure should not be tolerated. Control measures appear warranted and economically justifiable, particularly for the safety of those who happen to live in areas where natural radon flux is anomalously high.

The first step in control of any problem is its proper definition. In this regard, there are several techniques which can detect and measure the concentration of radon gas and its daughter products in air and water. The sampling of indoor or other "confined" air for trace quantities of gases is complicated by such things as changing air pressure, wind direction, temperature gradients, and ventilation rates. Therefore, alpha track detectors, daughter product collectors, and electronic alpha counting devices, operated over an extended length of time, are preferable for definitive surveys to the so-called transient or instantaneous detectors. Transient radon gas measurements, however, have their place in reconnaissance surveys and often prove very cost effective during "screening" to establish locations requiring additional attention. Selection and use of the various types of detectors for radon monitoring is a separate study and somewhat beyond the scope of this discussion. Thoughtful selection and use of off-the-shelf equipment will permit reliable detection of radon and measurement of its concentration precisely enough to define any health hazards that may exist.

Radon-related health hazards are essentially indoor problems that may be encountered in uranium, coal, fluorspar and some other mines; transportation tunnels; and hydro-electric underground excavations. Radon may be present in homes, and private and public buildings, and can be related to some industrial processes, such as super phosphate (fertilizer) manufacture and storage.

The current action level in the United States is 4 pCi/L. The action level is defined as the radon concentration above which provisions for control and mitigation are recommended. This action level implies an expected average of eight to nine decay events in a litre of air each minute. The Canadian standard is 800 Bq or about 21 pCi/L. Outdoor air at ground level, but not below the surface of the soil, has a radon content in the range of 0.1-0.25 pCi/L.

The radon in most buildings enters from the soil and rock beneath the foundations. Water, gas, sewer and electrical service lines often act as conduits for the gas into the lower levels of structures (*e.g.*, Bruno, 1983; Hess *et al.*, 1982). Radon can be introduced to kitchens and bathrooms in domestic water supplies. In some areas, as discussed earlier, this is the principal source of indoor radon. The technician carrying out radon surveys must consider all of these possibilities, and be prepared to identify unusual sources such as cinder block made from coal ash, some gypsum boards, construction stone, Portland cement, and phosphate fertilizer (*e.g.*, Nuclear Energy Agency — Organization for Economic Co-operation and Development, 1979; Stranden, 1983; Spengler and Sexton, 1983). In some rare cases, radon has been found to originate in industrial wastes from the manufacture of such things as instruments and watches with "glow-in-the-dark" dials.

The concentration of radon in any building will vary with changing air pressure. Decreasing barometric pressure, associated with approaching storm systems, will allow the soil to "exhale" radon gas, while approaching fine weather (high atmospheric pressure) tends to drive soil gases to depth and reduce the amount of radon present in buildings. Since most structures act as "airfoils" in winds, internal air pressure can be expected to vary with wind speed and direction. Each home, school or other "tight" building will tend to draw in or expel radon in response to these pressure changes. A house that is quite warm in a north wind, but drafty if the wind blows from the east, can be expected to have highest radon concentrations on still days or when the wind blows from the north, since there appear to be fewer air changes under those conditions.

Radon problems can be handled by remedial measures on existing structures, including sealing of service ways where they enter a building, by installing water traps in sewer lines, designing external discharge for foundation weeping tile drains, and by grouting around pipes and cables entering through a foundation. Construction material and building stones are normally only minor sources of radon gas. They can be painted with a rubber-based paint or removed from the building. While such prudent preventive measures are recommended as a matter of course, improved ventilation is usually all that is necessary to reduce radon concentrations from all sources to acceptable levels. Radon daughters can be removed from the air by encouraging plating out on walls, furniture and fixtures through use of a simple ceiling fan. A positive ion generator used in conjunction with a properly sized fan will remove 90-95% of all daughters from indoor air (Moeller, 1991; Gold, 1980; Sachs *et al.*, 1982; Hurwitz, 1981).

Modern energy-efficient buildings are more likely to accumulate radon gas from the underlying soils and rocks than older structures. Again, dilution is the main factor in maintaining acceptable levels. Some older buildings experience 5-20 air changes per hour, while modern designs often call for one air change per hour or less (Nazaroff *et al.*, 1981).

It was necessary to place impermeable plastic membranes (HDPE) and perforated plastic weeping tile grids set in screened crushed rock prior to pouring the floor slabs of certain recently constructed schools. Preconstruction soil gas radon surveying and geological inspection showed that these buildings were sited in areas underlain by uranium-bearing black shales that contributed more than 10,000 pCi/L radon to soil gas at some points in the construction area. The under-slab ventilation system reduces the relative air pressure so that air leakage tends to be from the building through the slab rather than the reverse, thus preventing radon entering the classrooms and service areas.

Pre-construction radon evaluation is advisable for energy-efficient buildings sited on rocks known to host uranium, or on tills and soils that have been derived from such rocks. The data collected in this evaluation will show if pre-construction preventive action is warranted. If so, relatively inexpensive measures may be taken to control possible entry of radon to the structure, thereby making costly remedial action unnecessary.

Control of radon in underground mines and tunnels is, again, largely a matter of adequate ventilation. However, water may be a significant transportation agent, as it was at St. Lawrence, Newfoundland, where serious radon-related health problems were recognized in the 1950s. In this case, radon gas was collected by water flowing through fractures in a modestly radioactive granite (<30 ppm U) and carried into the tunnels and stopes of the fluorspar mines where it accumulated in obviously dangerous concentrations. Radon-bearing ground water in a mine can be controlled in a variety of ways, and its initial exposure to air confined, where possible, to closed inactive areas. The water can then be removed from such collection areas in closed pipes rather than open ditches. Overall ventilation requirements can be reduced by tightly sealing off any openings not necessary to current operations. In some cases where radon sources are exposed on dry walls of underground openings, control may include painting the exposures with latex or epoxy to confine the radon until it has decayed naturally.

COSTS

Since radon detection, measurement and control measures are relatively simple, the cost of preventive and remedial action is relatively low. Regional airborne radon (gamma ray spectrometry) surveys may be done for less than $3.00/ha, providing there is a minimum of 10 km^2 per survey. Larger areas will be less expensive, perhaps as little as $0.75/ha. Regional radon in soil gas surveys can be expected to cost $6.00-150.00/ha, depending on sampling density, with similar costs for determination of radon in surface or ground water. A preliminary soil gas radon survey of a building site will cost in the order of $3000-5000, with the possibility of some additional expenditures to quantify the radon flux for design purposes if preventive measures are indicated. Simple sub-slab ventilation systems will add $4.00-7.50/m^2 to contruction costs, and membrane plus ventilation grids are likely to cost $15.00/m^2 of footprint.

Homes can be checked for radon using transient radon measuring equipment or passive detectors at a cost of less than $100, and more detailed determination of radon concentrations in water and indoor air will usually be less than $500, even when serious problems are found and measurement of radon daughters is required. Radon-proofing an average home can cost $500-5000 if done during construction, and $500-10,000 for established dwellings. In most cases, the costs have been found to fall in the $500-1500 range, with only very rare severe problem situations requiring larger expenditures (Hurwitz, 1991; Moeller, 1991).

Radon surveys of public buildings such as schools should be a two-phase procedure. The "screening" survey, designed to determine if there is above background concentration of the gas, can use inexpensive transient or passive methods. Only those buildings which are shown by screening surveys to justify additional attention need be tested using more precise methods. Schools are larger buildings than most homes, but the screening costs are not proportionally higher. A building with a 4000 m^2 footprint can be checked for $500-1500, usually during a weekend so there is no disruption of regular business. Detailed studies, which involve determination of working levels for precise health risk analyses, will require more time, and may cost several thousand dollars.

CONCLUSIONS

Radon is a naturally occurring radioactive gas generated during the spontaneous decay of uranium. Uranium is present in some quantity in almost all geologic materials and radon can, therefore, be expected as a normal component of all air in contact with the earth. Enclosed spaces with limited ventilation will collect the greatest amount of the gas. Energy-efficient buildings and underground openings often show elevated radon concentrations. In elevated concentrations, radon gas poses a defined health hazard to those exposed in both industrial and domestic environments. Domestic radon exposure is estimated to result in 10,000-15,000 excess lung cancer deaths per year in North America and is, therefore, considered to kill more people than any other single environmental hazard.

Regional and local sources of radon gas are easily defined by direct radon measurement using active or passive detectors or by radiometric (gamma radiation) surveys. The health hazard presented by any concentration of radon gas can be estimated quite quickly by relatively straightforward standard procedures.

The concentration of radon gas in indoor or underground air can be managed by a combination of simple techniques. In most cases, capital and operating costs of preventive or remedial measures are low.

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