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ASSESSMENT AND MANAGEMENT OF RESIDENTIAL RADON HEALTH RISKS: A REPORT FROM THE HEALTH CANADA RADON WORKSHOP

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Epidemiologic studies of uranium miners and other underground miners have consistently shown miners exposed to high levels of radon to be at increased risk of lung cancer. More recently, concern has arisen about lung cancer risks among people exposed to lower levels of radon in homes. The current Canadian guideline for residential radon exposure was set in 1988 at 800 Bq/m^3*. Because of the accumulation of a considerable body of new scientific evidence on radon lung cancer risks since that time, Health Canada sponsored a workshop to review the current state-of-the-science on radon health risks. The specific objectives of the workshop were (1) to collect and assess scientific information relevant to setting national radon policy in Canada, and (2) to gather information on social, political, and operational considerations in setting national policy. The workshop, held on 3–4 March 2004, was attended by 38 invited scientists, regulators, and other stakeholders from Canada and the United States. The presentations on the first day dealt primarily with scientific issues. The combined analysis of North American residential radon and lung cancer studies was reviewed. The analysis confirmed a small but detectable increase in lung cancer risk at residential exposure levels. Current estimates suggest that radon in homes is responsible for approximately 10% of all lung cancer deaths in Canada, making radon the second leading cause of lung cancer after tobacco smoking. This was followed by a perspective from an UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) working group on radon. There were two presentations on occupational exposures to radon and two presentations considered the possibility of radon*

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as a causative factor for cardiovascular disease and for cancer in other organs besides the lung. The possible contribution of environmental tobacco smoke to lung cancers in nonsmokers was also considered. Areas for future research were identified. The second day was devoted to policy and operational issues. The presentations began with a perspective from the U.S. Environmental Protection Agency, followed by a history of radon policy development in Canada. Subsequent presentations dealt with the cost-effectiveness of radon mitigation, Canadian building codes and radon, and a summary of radon standards from around the world. Provincial representatives and a private consultant were given opportunities to present their viewpoints. A number of strategies for reducing residential radon exposure in Canada were recognized, including testing and mitigation of existing homes (on either a widespread or targeted basis) and changing the building code to require that radon mitigation devices be installed at the time a new home is constructed. The various elements of a comprehensive national radon policy were set forth.

Radon is an inert gas formed by the radioactive decay of uranium-238, which is present in rocks and soils in the earth's crust. Radon can enter homes through tiny cracks and fissures in the foundation of homes, and is present in most homes at some level. Radon further decays into radioactive daughter products, which release alpha particles into indoor air. Upon inhalation such particles possess sufficient energy to damage DNA in lung tissue.

Epidemiologic studies of uranium miners and other underground miners have consistently shown miners exposed to high levels of radon to be at increased risk of lung cancer. These data, which are supported by animal and cellular studies, have resulted in the designation of radon as a known cause of cancer in humans by the International Agency for Research on Cancer (IARC, 1988). A combined analysis of 11 cohorts of over 60,000 underground miners conducted by Lubin et al. (1994), and updated by the U.S. National Research Council (NRC, 1999), provides a comprehensive assessment of lung cancer risks associated with radon.

Because radon has been shown to cause cancer in miners at high levels of exposure, there exists concern about lung cancer risks among people exposed to lower levels of radon in homes. The results of the 20 epidemiological studies of residential radon and lung cancer risk conducted to date have been mixed, with some studies suggesting a positive association between residential radon and lung cancer, and others providing equivocal or null results. However, a recent combined analysis of the seven large-scale residential case-control studies of radon and lung cancer conducted in North America provided evidence of a positive association between residential radon and lung cancer (Krewski et al., 2005), with the slope of the exposure-response curve compatible with that derived from the miner studies involving higher occupational exposures. Brand et al. (2004) recently estimated that some 6–16% of all lung cancer deaths in Canada could be attributable to residential radon, making radon the second leading cause of lung cancer after tobacco smoking. This estimate is comparable to similar estimates derived by the the U.S. National Research Council for U.S. homes.

Concerns about the risk of lung cancer due to the presence of radon in homes have resulted in the establishment of residential radon exposure guidelines in most developed countries throughout the world. The current Canadian residential radon exposure guideline is 800 Bq/m^3. Average residential radon concentrations in Canadian homes are approximately 28 Bq/m^3, much lower than the national guideline. There is considerable variation in radon concentrations among Canadian cities, with over 1% of homes in Winnipeg, the city with the highest average radon concentrations in Canada (approximately 125 Bq/m^3), estimated to be above the national guideline (Létourneau et al., 1994). Radon guidelines in most other countries are lower than that in Canada, with many European countries having guidelines in the range of 200–400 Bq/m^3 (SSI, 1999). The U.S. Environmental Protection Agency has established a national radon guideline of 4 pCi/L (equivalent to 148 Bq/m^3), over 5 times less than the Canadian guideline.

Because of continuing concerns about the lung cancer risks associated with residential radon exposure, Health Canada convened a 2-day workshop in Ottawa on 3–4 March 2004 to examine the latest scientific evidence and to discuss policy issues associated with radon. The workshop was attended by 38 scientists, regulators, and other stakeholders from Canada and the United States. The specific objectives of the workshop were:

1. To collect and assess scientific information relevant to setting a national radon policy.
2. To gather information on the social, political, and operation considerations in setting a national policy.

The presentations on the first day dealt primarily with scientific issues, whereas the second day was devoted to policy and operation issues. The various presentations are summarized here and placed within an overall framework of radon issues. At the end of each day, a facilitated discussion was held to focus on a set of prepared questions. The notes from these discussions were synthesized and paraphrased to give an overview of the participants' responses. Although no attempt was made to reach consensus on either scientific or policy issues relating to radon, all workshop participants reviewed the report prior to publication. The article closes with conclusions and recommendations from the workshop. The full proceedings of the workshop are available on CD ROM (Health Canada, 2004).

SCIENTIFIC ISSUES

Residential Radon Exposure and Lung Cancer

An overview from the UNSCEAR working group on radon was presented by Doug Chambers (SENES Consultants Ltd.), a member of the working group (Chambers, 2004). He noted that radon has long been recognized as an underground mining hazard; however, its recognition as a significant hazard in residential environments is a more recent development. In addition, exposure to thoron and its decay products should be considered in assessing the potential risks from radon exposure; the current estimate is that about one-third of radiation-induced lung cancers result from thoron. The UNSCEAR 2000 report had provided considerable information on the sources and the effects of radon. To review recent discussions on radon issues, UNSCEAR is drafting a new report: *Sources to Effects Assessment for Radon in Homes and Workplaces*. Chambers presented one figure from the report (Figure 1) that summarizes all of the recent studies on residential radon exposure. Although there are some studies showing no or negative effects at residential radon levels, most studies

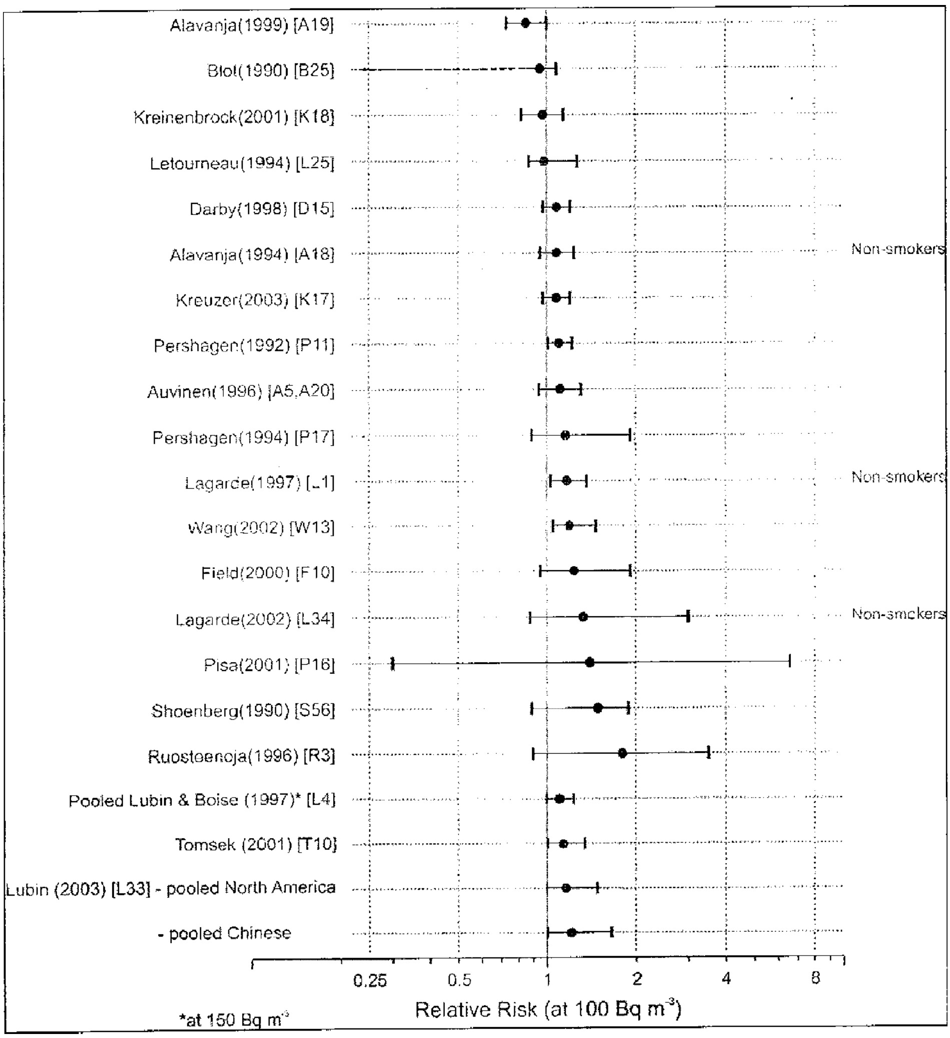

FIGURE 1. Comparison of relative risks at 100 Bq/m^3 in residential radon studies.

give a positive conclusion that radon increases the possibility of developing lung cancer.

In order to achieve greater statistical power from residential radon studies, it is necessary to combine or pool the results from the individual studies into a single analysis. Dan Krewski (McLauglin Centre for Population Health Risk Assessment) presented recent results on the combined analyses of seven North American residential radon and lung cancer studies (Krewski, 2004a). The project involved pooling the original data from seven North American case-control studies. The average living-area radon levels ranged from 26 to 150 Bq/m^3, with an overall average radon level of 70 Bq/m^3. Nearly all the radon measurements were based on 1-yr alpha-track monitoring. The analysis of all data showed no significant association between radon level and lung cancer risk. However, when the data were restricted to subjects residing in one or two residences during the exposure window, and at least 20 yr of coverage with α-track air monitors, the analysis revealed a positive association. The estimated excess odds ratio of lung cancers for time-weighted radon exposure in the 5–30 yr exposure time window was 0.096 with 95% confidence limits (–0.01, 0.26) for all data, and 0.176 with 95% confidence limits (0.02, 0.43) for restricted data, as shown in Figure 2. These results provide direct evidence of an association between residential radon and lung cancer risk, a finding predicted by extrapolation from miner data and consistent with results from animal and in vitro studies. His combined analysis also agrees well with the BEIR VI predictions.

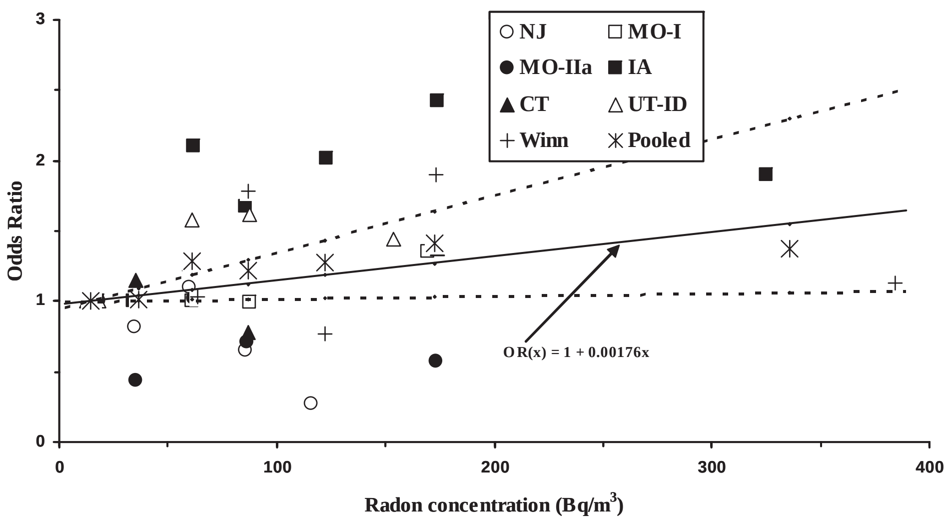

FIGURE 2. Odds ratios for categories of mean radon concentration within 5–30 yr exposure time window, the fitted model for the linear excess odds ratio (solid line), and its 95% confidence limits (dotted lines) for all studies combined. Data limited to subjects residing in 1 or 2 residences during the exposure window, and at least 20 yr of coverage with α-track air monitors.

Kevin Brand (McLaughlin Centre for Population Health Risk Assessment) discussed the implications of these findings for health of the Canadian population (Brand, 2004). He adapted the BEIR-VI methodology to the Canadian context and modified the assumptions to better reflect Canadian conditions. He was also able to quantify the implications of input uncertainty. His findings included an estimate of a lifetime risk ratio = 1.1, a population attributable risk = 10%, and life years lost = 0.097. This population attributable risk, applied to a Canadian population of 30 million, would lead to about 1800 lung cancer cases per year associated with radon. The BEIR-VI report gives a slightly higher risk for the United States, but this is explainable by higher mean radon exposures in U.S. homes.

The Uranium Miner Dosimetry Revisited

Rachel Lane (Canadian Nuclear Safety Commission) discussed the feasibility of a modern Saskatchewan Uranium Miners' study (Lane, 2004). The study would seek to estimate the risk of lung cancer as a result of radon exposure in an occupational cohort of miners from 1975 onward (present and future miners). Approximately 24,000 mine workers are estimated to have worked or will work in a Saskatchewan mine between 1975 and 2030. In 1993 the Joint Federal–Provincial Panel on Uranium Mining Developments in Northern Saskatchewan had recommended ongoing epidemiological studies of past, present, and future uranium miners to determine whether miners' lung cancer rates continue to be elevated compared to the general population. Lane described the methods and results of the feasibility study and outlined the process of the technical working group, peer review, and the steering committee. As a result of the feasibility study and peer review, it was concluded that the current occupational exposures to radon were too low and the statistical power of the study too weak to detect any effect, with either a cohort approach or a surveillance approach. In a sense this is a good-news story, since the increased use of open pit mining and better ventilation in underground mines have greatly reduced radon exposures.

Philippe Duport (International Centre for Low Dose Radiation Research, University of Ottawa) presented a study on the missing doses in uranium miner exposures, namely, gamma radiation and radioactive dust (Duport, 2004). Using data from French uranium mine studies going back to 1956, Duport concluded that exposure data in uranium mines are highly unreliable and have consistently ignored a large, sometimes predominant fraction of the lung dose. He suggested that at least half of occupationally induced lung cancers in uranium miners may not be due to radon decay products but to gamma radiation, radioactive dust, and nonradioactive carcinogens in the mine environment. He also questioned radiation and tissue weighting factors and dose-response linearity. With regard to indoor radon, Duport expressed a concern that concentrations of radon decay products may be much higher in the breathing zone than that in the zone measured by a fixed device. The meaning of risk per unit radon exposure would therefore be questionable. A comparative dosimetry of radon in mines and homes would help to resolve the issue, but it would consider only the effects of particles, not external gamma exposure.

Discussion It was noted that cancers at sites other than lung have not shown up in the miner studies. If one applies the 5% per Sv cancer risk coefficient, then there should have been other cancers. Although there were other cancers observed in the miners, the cases were too few to be significant. Arguably, an alpha particle has to hit a cell in order to produce a cancer. If radon or its decay products were not being transported to other organs [see next paragraph], then one could explain the lack of cancer at other sites. But even at that, one would have expected the gamma dose in the uranium mines to have produced excess cancers at other sites.

Other Health Effects of Radon

The link between radon and lung cancer appears well established. But could radon be a factor in causing cancer at other sites in the body? Richard Richardson (Atomic Energy Canada Limited) provided information on the dosimetry of radon and progeny in body tissues and pointed out that solubility is the key parameter in radon dosimetry (Richardson, 2004). There is an approximately 10-fold uncertainty in radon solubility in fat, which influences most nonlung dosimetry and the consequent risk assessment (Richardson et al., 1991). Accurate solubility coefficients in fat and nonfat tissues will allow better risk assessment of nonlung cancers and noncancer diseases induced by radon. Richardson reviewed the transport kinetics of radon and progeny in the body. Most radon is in an attached form and when inhaled deposits in the lung; the remainder is absorbed to blood within hours. From blood the radon diffuses into intracellular fluids and fat and nonfat cells. The radon concentration in tissue is limited by its solubility and by biochemical properties in bone. A new experiment is being designed to assess radon solubility by in vivo whole-body counting. Two previous studies carried out in the 1950s gave greatly differing results for the radon solubility in fat; a new study is needed with clearly defined protocols.

The workshop also considered recent reports of associations between radiation and noncancer disease mortality. John R. Johnson (IDIAS, Inc.) discussed a possible link between cardiovascular disease (CVD) mortality and exposure to radon. He summarized his previous work on this topic (Johnson et al., 2003; Johnson & Duport, 2004). The literature gives an excess relative risk for CVD of 0.38 (per Sievert) estimated from A-bomb survivor data and 0.79 from data of Chernobyl emergency workers. No effect was apparent in data from the British radiologists. Johnson mentioned Jan Zielinski's earlier presentation on cardiovascular mortality in the Canadian National Dose Registry cohort (Zielinski, 2002), which showed an increase in CVD mortality with radiation dose. Johnson concluded that radiation, including radon, does indeed cause CVD; however, the risk needs to be evaluated in nonuranium mines and in homes.

Discussion Participants pointed out that the contribution of radiation to CVD will change as the population ages and becomes more susceptible to radon-induced effects. The relative risks may well be the same for lung cancer and CVD, but mortality is higher for CVD because the baseline number of cases is higher. However, there are so many risk factors for CVD (smoking, obesity, genetic susceptibility, etc.) that it is difficult to pinpoint a clear cause–effect relationship.

Other Causes of Lung Cancer in Non-smokers

Are all lung cancer cases in nonsmokers caused by radon exposure? Murray Kaiserman (Tobacco Control Programme, Health Canada) addressed the issue of environmental tobacco smoke (ETS), which includes sidestream smoke (emanating directly from a burning cigarette) and secondhand smoke (having been exhaled from the lungs of a smoker) (Kaiserman, 2004). ETS is classified as a Group A carcinogen by the U.S. Environmental Protection Agency. Like mainstream smoke, it is composed of over 4000 chemicals, including at least 50 carcinogens. In addition, smokers inhale lesser amounts of carcinogens than are emitted into the environment by a smoldering cigarette. Exposure to ETS results in a wide range of health outcomes, including low birth weight, sudden infant death syndrome (SIDS), respiratory effects in children, middle ear infection, asthma induction, asthma aggravation, bronchitis or pneumonia in infants and toddlers, lung cancer, nasal sinus cancer, and ischemic heart disease. It is estimated that, in 1998, the smoking attributable lung cancer mortality for both sexes was approximately 14,000, or about 86% of all cases. ETS-attributable lung cancer deaths were estimated to be approximately 360, or about 2% of all cases, which should be compared with 1800 cases per year attributable to residential radon exposure.

Discussion A question was raised about the interaction between smoking and radon in producing lung cancer. The BEIR-VI report had concluded that the interactive effect is more than additive but less than multiplicative. Because of this synergistic interaction, nearly 90% of the deaths attributable to residential radon occur in smokers. However, because of their lower baseline lung cancer rates, the relative risk of lung cancer mortality is notably greater in nonsmokers than in smokers. The interactive effect may be changing over time, since the "engineering" of cigarettes means that the mix of carcinogens in tobacco smoke is continuously changing.

Participants also considered whether there is any contribution to lung cancer from urban air pollution and whether there might be a pollution/radon interaction. According to Bernie Cohen's analysis (Cohen, 1997), the Rocky Mountain states have more radon than New England, but New England has more lung cancer. However, ecologic studies such as these are difficult to interpret, since the effects of radon and air pollution have not been clearly separated. The effects of aerosols in the homes environment (e.g., cooking fumes, dust/skin flakes) should also be considered. A comparative analysis of the dosimetry of radon in mines and homes might provide some clarification. The American Cancer Society has proposed a study of environmental radon and air pollution along with other risk factors such as arsenic.

General Discussion of Scientific Issues

1. *Is the linear-no-threshold (LNT) hypothesis valid for radon-induced lung cancer? If there is a threshold, does it extend downward to residential levels of radon*?

The participants concluded that a threshold cannot be ruled out, but it may not be possible to specify exactly where it lies. Any threshold is likely to be dose-rate dependent. The identification of a threshold is further complicated by the fact that a radiation-induced lung cancer is indistinguishable from a smoking-induced cancer. Epidemiology alone cannot settle this question; the data are consistent with both a threshold and an LNT hypothesis. One would also need knowledge of biological and biophysical mechanisms to resolve the issue. For example, can a single alpha particle produce lung cancer? What is the link between DNA damage and cancer?

Some insight is provided by considering the conversion from radon exposure in working level months (WLM) to radiation dose in millisieverts (mSv). With the following assumptions:

Dose conversion factor = 3.88 mSv/WLM for the general public (ICRP, 1993).
Equilibrium factor between radon and its short-lived progeny = 0.4.
Household occupancy factor = 80%.
Household radon level = 200 Bq/m^3.

one obtains an annual dose estimate of 3.5 mSv and a cumulative dose over 70 yr of about 250 mSv. This is greater than the 100 mSv value at which the association between cancer and radiation exposure begins to become significant.

2. *Can radiobiology and microdosimetry help to understand the effects of radon*?

The participants agreed that these can provide additional insights into mechanisms. If radon behaved like oxygen, it would be distributed uniformly throughout the lungs. However, most of the dose to the lungs is from radon progeny, which are generally attached to solid particles. A distinction needs to be made between inhaled progeny and the progeny resulting from the decay of radon once it enters the lungs. Furthermore, there are different types of cells in the lungs, so it is not sufficient simply to compute an average doses to all cells. The ICRP-66 lung model and its annexes make lung dosimetry feasible. The model is more sophisticated than previous versions; the target cells have been identified and their depth below the surface specified.

The participants discussed the possible influence of the bystander effect on lung dosimetry. If this effect does indeed occur, perhaps we are returning to the concept of average dose to the whole tissue. Also, a bystander effect could induce an adaptive response in the irradiated tissue.

The effects of nanoparticles also need to be considered in lung dosimetry. Nanometer-size hydrated particles have different behaviors from those of micrometer sizes. Nanoparticles may be transmitted through the lining of the lungs (see Marsh et al., 2002). If a macrophage picks up a particle, it may affect other cells, but only close neighbors. Ultrafine particles have been treated extensively in occupation literature, for example, for welders. Pharmaceutical companies make products using ultrafine particles, for example, symbacore for asthma.

There have been some suggestions that the radiation weighting factor for alpha radiation should be reduced from 20 to 10 in order to resolve the discrepancy between radon dosimetry and epidemiology.

3. What are the priorities for future research?

- We need a better understanding of biological mechanisms. Biomarkers of exposure should be studied. The relation between exposure to radon and the amount absorbed by the body should be clarified.
- We should reexamine the miner studies and add all the exposures (radiation + chemical) to that of radon. Silicosis may alter the body's response to radon. Noncarcinogens may lead to interactions with radon; the relation between exposure to radon and the amount absorbed by the body should be clarified.
- There is a need to identify radon-prone areas in the country, perhaps in the form of geological survey maps. Although this would be expensive, the United States and United Kingdom make extensive use of such maps in developing public policy. Maps will indicate what is on the ground but not what is in the house.
- Perhaps the time has come to update the 1978 cross-Canada radon survey. The Oka study was a high-resolution survey. But a broad, low-resolution survey may miss the hot spots. The influence of building materials should be considered, although the Winnipeg study showed building material to be a poor predictor of radon levels.
- Electrostatic drift in radon measurements should be examined.

POLICY AND OPERATIONAL ISSUES

Overview of Worldwide Radon Guidelines

Jing Chen (Radiation Protection Bureau, Health Canada) presented an overview of radon guidelines from around the world (SSI, 1999). She recalled that the Canadian residential radon guideline of 800 Bq/m^3 was established in 1988, as a recommendation, not a regulation. Radon action levels from around the world are shown in Figure 3, a and b, for existing and new homes, respectively. It can be seen that the Canadian guideline tends to stand above the others, especially for new homes. Only Switzerland has a higher value for new homes, at 1000 Bq/m^3, but this is an enforceable standard. The recommended value in Switzerland is 400 Bq/m^3.

ICRP Publication 60 (ICRP, 1991) states that the best choice of an action level for dwellings would involve a significant but not unmanageable number

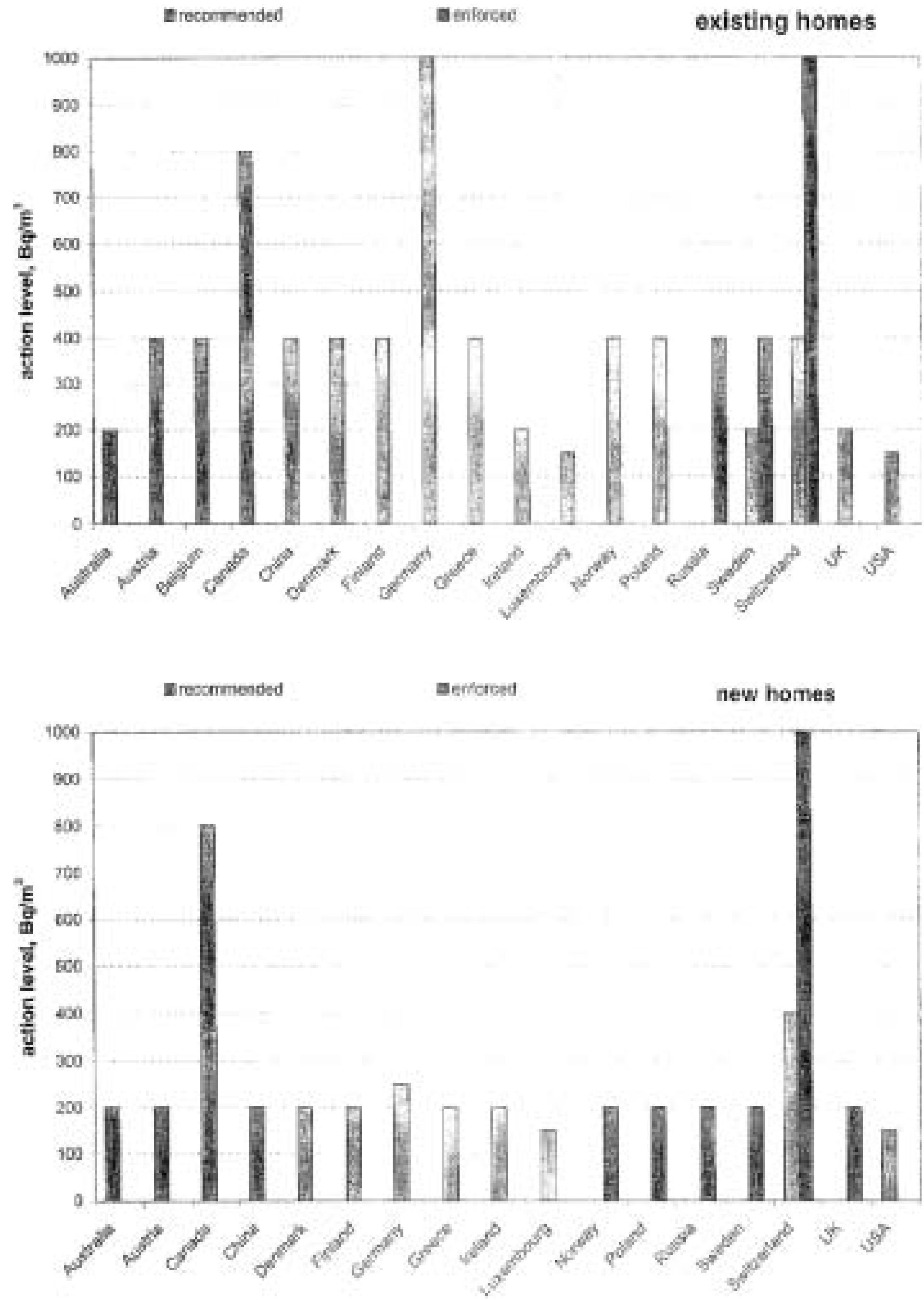

FIGURE 3. (a) Radon action levels for existing homes. (b) Radon action levels for new homes.

of houses requiring remedial work. That document did not give a numerical value, but ICRP Publication 65 (ICRP, 1993) recommended an optimized level in the range of 200–600 Bq/m^3, which correspond to annual effective doses of 3 to 10 mSv. Chen concluded that the Canadian residential radon action level of 800 Bq/m^3 needs to be harmonized with ICRP recommendations.

Radon Policy and Practices in the United States

Philip Jalbert of the U.S. Environmental Protection Agency described the U.S. experience with two decades of radon policy (Jalbert, 2004). He took as his starting point the recent U.S. The U.S. EPA estimate that 21,100 (13.4%) of the 157,400 U.S. annual lung cancer deaths were radon related. Of these 21,100 deaths, 18,200 were ever-smokers and 2900 were never-smokers. The U.S. EPA considers exposure to radon in indoor air to be the second leading cause of lung cancer after smoking. The U.S. EPA and the Office of the U.S. Surgeon General strongly recommend that Americans test, and fix their homes when radon levels are 4 pCi/L (150 Bq/m^3) or more. At this level the risk of radon-related lung cancer is estimated to be 23 per 1000 persons for the general population with a constant lifetime exposure. For current smokers the lifetime risk rises to 62 per 1000 and for never-smokers it is 7 per 1000.

The U.S. EPA estimates that about 100 million U.S. homes need to be tested for radon, and that 6 million are expected to exceed the 4 pCi/L guideline. A radon test can cost $10 to $50 with a do-it-yourself kit with mail-in, or $75 to $350 by a professional home inspector. In the period 1984–2002, approximately 700,000 homes were mitigated and an additional 1 million homes were built with radon-resistant features. Subslab depressurization in existing homes has proven to be the most cost-effective mitigation technique. At an average cost of US$1200 per home, it can achieve a radon level <2 pCi/L 70% of the time. If all homes were mitigated to this level, 450 lives would be saved annually at a cost of $400K per life saved. Radon-resistant features in new homes can add $350 to $500 to the cost of the home.

The U.S. EPA federal radon program is based on a strategy of voluntary action, public education, and partnerships with other federal agencies, states, local governments, nonprofit organizations, educators, real estate organizations, and the radon services industry. One of the best opportunities to test for radon is during real estate transactions. An estimated 34 states include radon in mandatory property condition disclosure, and 12 states require licences for radon testing services. Since radon testing and mitigation are not mandatory in the United States, the U.S. EPA has invested heavily in public education programs. The greatest obstacles to public acceptance are a sense of complacency about radon risks and the costs of testing and mitigation, which in most cases must be borne by the homeowner.

In general, the U.S. EPA has paid less attention to levels of radon in drinking water. The major impact from radon in water is not through ingestion but through inhalation, once the radon has diffused out of the water and into the air of a home. In 1999 the United States proposed a rule (64 FR 59246, 2 November 1999) that would establish two standards for radon in drinking water: a maximum contaminant level (MCL) (300 pCi/L), and an alternate MCL (AMCL) (4000 pCi/L). The intent of having two standards is that states and utilities would have the option of treating their water to the AMCL if they also implement a risk reduction program for radon in indoor air.

Radon Policy and Practices in Canada

Ernest Létourneau (former director of the Radiation Protection Bureau, Health Canada) described the evolution of radon policy in Canada during the past three decades (Létourneau, 2004). In the early 1970s, the chief radon concern in Canada was the level in mines. However, in 1975, high radon levels were discovered in many homes and several public schools in the town of Port Hope, Ontario. This radon resulted from the use of contaminated backfill material around buildings that had originated as wastes from the radium (and later uranium) refinement facility in the town. In order to facilitate cleanup of the backfill, it was necessary to establish what a "normal" radon level is. Surveys in the nearby town of Coburg showed that radon in homes rarely exceeded 0.02 working levels (WL), and this value was adopted by the Federal-Provincial Task Force on Radioactivity. If one assumes an equilibrium ratio of 0.5 for short-lived progeny to the radon parent, this criterion corresponds to a radon concentration of 4 pCi/L (148 Bq/L), the current value adopted by the U.S. Environmental Protection Agency.

Between 1978 and 1980, Health Canada completed a cross-Canada radon survey involving 14,000 homes. Four percent of the homes were found to exceed the 0.02 WL criterion. At that time, the Federal–Provincial Sub-Committee on Radiation Surveillance began to consider the question of a nation-wide radon standard. In 1985 a draft guideline of 800 Bq/m^3 was proposed and was adopted by the federal and provincial deputy ministers of health in 1988. The guideline states that "remedial measures be taken where the level or radon in a home is found to exceed 800 Bq/m^3 as the average annual concentration. Because there is some risk at any level of radon exposure, home owners may wish to reduce levels of radon as low as practical." The rationale for this value was based on the concept that the risk from household radon should not exceed the risk considered acceptable in uranium mines.

The publication of two landmark papers in 1992 and 1994 supported the wisdom of setting the guideline at 800 Bq/m^3:

- Cost-effectiveness of Radon Mitigation in Canada (Létourneau et al., 1992).
- Case-control Study of Residential Radon and Lung Cancer in Winnipeg, Manitoba, Canada (Létourneau et al. 1994).

However, public attitudes on acceptability of risk have changed over the years. In 1995 Health Canada proposed lowering the radon guideline to 400 Bq/m^3 in order to bring it more in line with worldwide values; however, the proposal was not accepted by the Federal–Provincial Sub-Committee on Radiation Surveillance.

Don Fugler of Canada Mortgage and Housing Corporation (CMHC) presented results on building research pertinent to radon risks in Canadian housing (Fugler, 2004). CMHC has been researching residential indoor radon for 20 yr. This includes work on isolating houses from radon entry by providing a protective boundary at the foundation. They found that plastic laid on top of the gravel, prior to pouring the concrete floor, was an effective way to stop soil gas entry through the cracks that developed in the concrete. This was true even if the polyethylene was punctured either intentionally or due to job site inattention. The wet concrete would flow through the punctures and provide a seal. Due to the success of this research, a requirement for plastic under slabs was introduced into the National Building Code in 1990 and retained in the 1995 edition.

A project for the finishing of existing basements, which used wall and floor cavities ventilated to the outside, was also shown effective at preventing the entry of radon and moisture into house air. CMHC sponsored research into the radon emissions of Canadian building materials which showed that their contribution to typical housing was minimal (0.2 to 15% of total radon in the home, depending on loading). CMHC has a wide selection of research on soil gas problems other than radon. These studies may be of use to the radon community, as the soil pressures, entry mechanisms, and remedial measures are all somewhat similar.

Fugler concluded that, although radon has been assessed as a significant problem in the past, it is not currently considered a significant issue with builders and code officials. There are some proposed changes to codes and standards that will increase the permissible amounts of house depressurization and thereby increase radon concentrations in new homes.

Cost-Effectiveness of Radon Mitigation

Three short presentations examined the cost effectiveness of comprehensive strategies for reducing exposure to radon gas in indoor air in Canadian homes. Jan M. Zielinski (Health Canada) concluded that any comprehensive programme to reduce exposure to environmental radon would be extremely expensive, particularly when considered in relation to other public health programs (Zielinski, 2004). Nonetheless, testing of homes at the point of sale and installing subslab suction equipment to reduce exposure to indoor radon where necessary appeared to be a relatively cost-effective mitigation strategy. Because of regional differences in radon levels in Canada, radon mitigation would be more cost-effective in some areas than others. In general, radon mitigation was found to be most cost-effective in cities with relatively high levels of radon.

Dan Krewski of the McLauglin Centre for Population Health Risk Assessment, University of Ottawa, presented results of an opinion survey conducted by Jerry Spiegel at University of British Columbia (Krewski, 2004b). The survey measured the willingness of the public to pay for mitigation at various concentrations of household radon (Figure 4). It can be seen that the expressed preference of

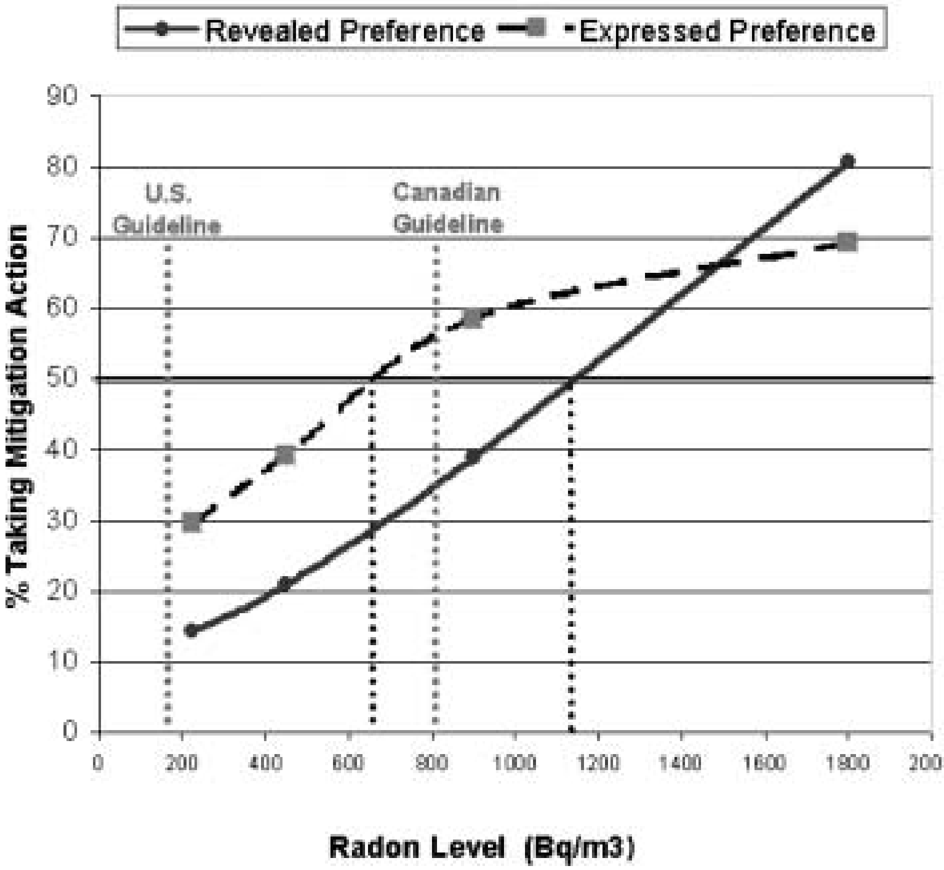

FIGURE 4. Probability of reducing radon risk, expressed versus revealed preference (Spiegel & Krewski, 2002).

willingness to pay rose from 30% of respondents at 200 Bq/m^3 to 60% at 800 Bq/m^3. However, the revealed preferences (as determined by what they had done and spent to reduce their exposure to radon) were lower, at 15% to 40%, respectively. The radon concentration would have needed to exceed 1100 Bq/m^3 before 50% of respondents took any action.

Michael King (Applied Research & Analysis Directorate, Health Canada) described an ongoing project to carry out an economic evaluation of residential radon mitigation in Canada (King, 2004). The evaluation will consider five comprehensive national strategies to control radon exposure within Canadian dwellings:

1. Screen all existing homes.
2. Building code change.

3. 1 + 2.
4. Screen home at point of sale.
5. 2 + 4.

The evaluation will also consider three action levels (800, 400, and 200 Bq/m^3), three levels of homeowner compliance (100%, 50%, 10%), and two levels of mitigation effectiveness (90%, 70% reduction).

The BEIR VI exposure–age–concentration model will be applied in a probabilistic simulation, adapted to the Canadian context. Life table methods will be used to project savings in lung cancers, with consideration of the age–sex composition of the Canadian population, population growth, competing causes of death, uncertainty in the estimation of exposure and risk, and a delay in the expression of health benefits resulting from reduced population exposure to radon. The study will update the work of Létourneau et al. (1992), comparing each strategy in terms of both estimated total cost, and cost per lung cancer averted, life year, and quality-adjusted life year gained. Publication is expected in the fall of 2004.

Provincial and NGO Perspectives

Quebec Jean-Claude Dessau (Institut national de santé publique du Québec) reported the findings of a Quebec advisory panel "Groupe de travail sur le Radon," which involved a health risk assessment and critical analysis of intervention strategies (Dessau, 2004). He pointed out that the current knowledge of specific conditions in Quebec houses is still very limited. A survey by Levesque et al. (1995) of 900 Quebec residences showed an average basement radon concentration of 34.6 Bq/m^3 and a first floor concentration of 18 Bq/m^3. Higher radon levels are known to occur in the Oka, Saint André, Mont-Saint-Hilaire regions. In Oka, an area impacted by a former niobium mining operation, a survey of 241 homes carried out between 1996 and 2002 showed radon concentrations approaching 10,000 Bq/m^3 in some homes. The geometric mean values in the 3 zones adjacent to the mining area were 131, 285 and 490 Bq/m^3. Initially, it was estimated that the cost of mitigation in the Oka area would be $3000 (Canadian) per home, with 75% being borne by the government. A pilot mitigation, carried out on 8 of the homes, showed that the cost would rise to $5000 per home. Only a few minor mitigation activities have been carried out to date.

Dessau discussed various options for reducing radon effects in Quebec. A compulsory province-wide screening program with mitigation of all buildings to less than 150 Bq/m^3 could save 71 out of an estimated 430 lung cancer cases per year due to radon. This represents a reduction of 16% in the number of cases. A more limited program of compulsory screening in schools would give the same percentage reduction; however, the number of lung cancer cases prevented would only be 2.3 per year out of a total of 14 cases.

Nova Scotia Patrick Wall (Nova Scotia Environment and Labour) briefly summarized the radon experience in Nova Scotia (Wall, 2004). Since 1976, 10 surveys have been undertaken of radon in air and water, and maps of the province have been produced showing likely areas of radon elevation. A 1990 study of radon in indoor air showed that out of 719 homes tested, 12% showed radon concentrations in excess of 185 Bq/m^3, 5% in excess of 370 Bq/m^3, and 3% in excess of 800 Bq/m^3. He also pointed out that in a recent survey of drinking water in 186 schools, an excess of dissolved radon in the water had given rise to excess ^{210}Pb concentrations.

British Columbia David Morley (British Columbia Centre for Disease Control) reported British Columbia's experience with radon surveys in 1378 homes and 375 schools (Morley, 2004). Table 1 summarizes the results for the homes and schools. Note that in the Castlegar area, 15% of schools exceeded the Canadian guideline. In this same area 38% of schools and 41% of homes exceeded 150 Bq/m^3. There were also exceedences in the Nelson area. Table 2 summarizes the effectiveness of radon mitigation measures in the schools. Subslab ventilation reduced radon levels by 81 to 98%, and simple sealing of floors produced reductions of 45 to 69%. Morely also pointed out a problem

TABLE 1. Radon Levels in British Columbia Schools and Homes

School district	Mean radon in schools (Bq/m^3)	Mean radon in homes (Bq/m^3)	Percent of shools above 150 Bq/m^3	Percent of homes above 150 Bq/m^3	Percent of schools above 800 Bq/m^3
Kelowna	26	85	4	7.8	0
S. Okanagan	81	—	14	—	0
Penticton	38	107	5.6	16	0
Castlegar	100	240	38	41	15
Prince George	30	89	4.5	29	0
N. Thompson	137	159	70	53	0
Vernon	57	74	5	9.2	0
Nelson	164	122	45	20	5
Trail	57	111	13	16	0

TABLE 2. Effectiveness of Mitigating Radon in School Buildings

School	Method of mitigation	Initial radon (Bq/m^3)	Mitigated radon (Bq/m^3)	Percent of reduction
West Kootenay School Board Office	Subslab ventilation	1413	26	98
Okanagan+ #1	Sealing	396	220	45
Okanagan+ #1	Sealing and subslab ventilation	396	30	92
North Thomspon	Subslab ventilation	308	52	82
West Kootenay #1	Subslab ventilation	1430	140	90
West Kootenay #2	Sealing	1238	236	81
West Kootenay School Daycare	Sealing	662	140	69
East Kootenay #1	Sealing	3237	60	98

in BC fish hatcheries, where dissolved radon in the water was leading to elevated radon concentrations in air in some working areas of the hatchery.

Ontario Ken Gilmer (Ontario Ministry of Labour) discussed the work of Radiation Protection Service (RPS), the only Ontario government agency with the capability to conduct radon measurements (Gilmer, 2004). Historically, the RPS has been involved with various radon studies in the Elliot Lake, malvern, and Port Hope areas, as well as Ontario fish hatcheries and uranium mines. However, radon levels in Ontario homes and businesses are not routinely measured by Ontario government agencies at the present time and there are no plans to conduct surveys. The government believes that the current Canadian guidelines of 800 Bq/m^3 is seldom approached in workplaces. Mr. Gilmer pointed out that the provinces do not have the resources to conduct appropriate research and studies before establishing new guidelines. They look to Health Canada to identify issues associated with public health and to establish appropriate guidelines for public exposures to radioactivity. He noted that the federal cross-Canada radon survey was carried out 25 yr ago, and that the survey should be updated in order to identify significant "radon prone" areas in Canada.

Radiation Safety Institute of Canada The Radiation Safety Institute of Canada is an independent nonprofit organization that provides radiation dosimetry in Canada for radon and thoron progeny and for long-lived radioactive dust. Fergal Nolan, the institute's president, drew attention to increasing international concern over workplace exposure to environmental radon and thoron, as well as radon in the home (Nolan, 2004). He noted two erroneous assumptions that in the past have negatively affected radon policy development in Canada. The first is that radiation, radon, and the nuclear energy industry are somehow inextricably linked in the public's mind, leading to an oversensitivity in policy development to possible effects on the public's perceptions of the nuclear energy industry. The second assumption is that "if it's radiation, the government must pay," leading to an exaggerated public policy emphasis on potential public-sector costs. He felt that these assumptions are obstacles to an effective public health policy on radon and should be dispelled. With regard to the current Canadian guideline, Dr. Nolan stated the institute's views that Canada's current public policy position is untenable, that sufficient scientific and public policy work has already been conducted in Canada and in other countries for Canada to act, and that authorities should proceed without delay to revise Canada's radon policy to bring it in line with international public health guidelines.

General Discussion of Policy and Operational Issues

1. Upon what considerations or criteria should a radon guideline be based?

The participants agreed that the first requirement was to define the goal in setting a guideline. What are we trying to accomplish? For example, automobile emission standards strive to achieve a certain percentage reduction in emissions. Following that, a complete risk assessment and analysis should be carried out. It is helpful to make a clear distinction between what is an acceptable risk versus what is unacceptable. One should also distinguish between personal risk and population risk. The population risk will be reduced only if a large portion of the population can be persuaded to comply with the guideline. Participants were reminded that setting a guideline and explaining it to the public are two different things. When setting a guideline we should not assume that the government will pay; it is the homeowner who pays.

We should be asking ourselves whether a guideline or regulation is enforceable if it is lower than most of the measured levels. There is a parallel with the Ontario guideline of 200 ppm for lead in soil. This level is often exceeded in urban soils and the guideline is not really enforceable.

We should also remember that guidelines tend to develop into regulations. If we do not enforce, someone else will. This is pertinent to federal–provincial jurisdictional issues. Some concern was raised by the prairie provinces that, if the federal government lowers the guideline, the poorer provinces may have to pay. On the other hand, British Columbia felt that a lowering of the guideline would not lead to a large number of mitigations.

We should be considering whether a guideline is consistent with other national or international jurisdictions. International consistency may increase compliance with a guideline. For example, compliance with a radon guideline in the European Union went up once it was known what the U.S. guideline was.

2. Who are the stakeholders in setting a radon guideline?

The participants felt that the following were all legitimate stakeholders in establishing a radon guideline, and that they should be consulted during the discussion process:

Federal departments

- Health Canada with primary responsibility for public health.
- The Canadian Nuclear Safety Commission (CNSC) with responsibility for the licensing of nuclear facilities.
- Human Resources Development Canada (HRDC) with responsibility for occupational exposures through the Canada Labour Code.
- Canada Mortgage and Housing Corporation with responsibility for building research and setting of building codes.
- The Low Level Radioactive Waste Management Office (LLRWMO) with responsibility for managing historic wastes, including radon-emitting wastes.
- Other federal departments and agencies with responsibility for housing stock (e.g., Indian and Northern Affairs Canada, Department of National Defence, Parks Canada).

Provincial and municipal governments

- The health and environment ministries of all provinces and territories.
- Municipalities and the Federation of Canadian Municipalities.
- Local medical officers of health.

Industry and commerce

- The building industry.
- Real estate companies.
- Banks and mortgage companies.
- Life and home insurance companies.
- Radon testing services.
- Home and building inspectors.

Advisory bodies

- Radiation Safety Institute of Canada.
- Canadian Radiation Protection Association.

3. What are some of the difficulties in achieving compliance with a radon guideline and how might they be overcome?

The main problem is how to find and deal with the homes with very high radon levels. Is the problem big enough to justify a massive public education program? The best way to achieve compliance with radon testing is during real estate transactions. In some states of the United States, disclosure of radon levels, if known, is mandatory at the time of sale.

Nonetheless, testing by itself does not necessarily lead to remediation. An industrial competence for radon remediation must first be established. Some European Countries offer financial incentives to help alleviate remediation costs. During the 1970s and 1980s the Canadian Home Insulation Program gave grants to homeowners to assist with energy conservation measures.

4. What are the elements of a comprehensive national radon program?

The participants agreed that more was involved than merely setting a numerical guideline. Explaining risks to the public is an important element. Policy goals must be clear. Is the goal to reduce lung cancer deaths or to provide information to allow the public to make informed decisions? Participants agreed that both goals were legitimate.

Another element is to provide advice to the public on when and how radon testing should be carried out and on the effectiveness of radon remediation strategies. Certification of radon testing and remediation services could be an important function here. Priorities could be set for remediation. For example, the province of Quebec recommended remediation of schools as a top priority.

More information is needed on current radon levels (e.g., through radon maps, similar to those used in the United States or United Kingdom). It may be time to update the 1978 cross-Canada radon survey. The survey still represents the best database we have in Canada to date. It was a population-weighted survey. However, there are shortcomings in the grab-sampling method used at that time. In Winnipeg, an average radon concentration of 185 Bq/m^3 in the basements but was 30% less in living areas of the homes.

CONCLUSIONS

Based on the presentations made at the workshop and the subsequent discussion among the workshop participants, the following conclusions may be drawn.

Evidence of Lung Cancer Risk

- Studies of underground miners have consistently demonstrated increased lung cancer risks at high occupational radon exposure levels.
- Recently completed pooled analyses of residential radon studies have confirmed a smaller but detectable increase in lung cancer risk at residential exposure levels.
- These findings are supported by similar findings in experimental animals and cellular test systems, and have led to the conclusion that radon is a cause of cancer in humans.
- Current estimates suggest that radon in homes is responsible for approximately 10% of all lung cancer deaths in Canada, making radon the second leading cause of lung cancer after tobacco smoking.
- Because of the synergism between radon and tobacco smoke, the preponderance of lung cancer deaths attributable to residential radon in Canada occur in smokers.
- Although the number of radon-related lung cancer deaths (approximately 1500 in Canada annually) is higher in smokers than in nonsmokers, the relative risk of lung cancer is higher in nonsmokers than in smokers.

Radon Exposure Levels

- Residential radon levels in most Canadian homes are low, averaging about 28 Bq/m^3 across Canada.
- Because radon enters homes primarily through tiny cracks and fissures in the foundations of homes, radon levels in apartments above the third story are essentially nondetectable.
- There exists considerable variation average radon levels in cities across Canada.
- Radon levels in similar homes in the same region can vary markedly.
- Radon levels can vary within the same home, and are generally about 50% higher in the basement as compared to the living area.

Residential Radon Exposure Guidelines

- The current Canadian guideline for residential radon exposure is 800 Bq/m^3.
- Less than 1% of all homes in Canada have radon levels above the current Canadian residential radon exposure guideline.

Radon Mitigation

- Residential radon concentrations can be effectively reduced through a variety of means, including the installation of subslab depressurization devices.
- Such devices are more economically installed at the time a home is constructed.
- Studies of willingness-to-pay to reduce residential radon concentrations in Canada suggest that people are reluctant to spend appreciable amounts of money to reduce radon levels in their home, and are likely to do so only at radon concentrations exceeding the Canadian radon exposure guideline by a substantial amount.
- Relatively few homes in Canada have radon mitigation devices installed.
- Cost-effectiveness studies have revealed that the cost of averting a lung cancer death caused by radon varies dramatically with the level of radon in homes, with radon mitigation being notably more cost-effective in areas of high as compared to low radon areas.
- A number of strategies for reducing residential radon exposure in Canada can be contemplated, including testing and mitigation of existing homes (on either a widespread or targeted basis), changing the building code to require that radon mitigation devices be installed at the time a new home is under construction, and testing a mitigation of existing homes prior to sale.

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