Radon and Lung Cancer

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ACS CPS – American Cancer Society Cancer Prevention Study

AR – attributable risk

ASMR – age-standardized mortality rate

BEIR VI – sixth Committee on Biological Effects of Ionizing Radiation

CADTH – Canadian Agency for Drugs and Technologies in Health

CCHS – Canadian Community Health Survey

CMA – census metropolitan area

DES – discrete event simulation

DNA – deoxyribonucleic acid

EAC – exposure-age-concentration model

EOR – excess odds ratio

EPA – Environmental Protection Agency

EQ5D – a standardized instrument used as a measure of five dimensions of health-related quality of life developed by the EuroQol group.

ERR – excess risk ratio

GBD – global burden of disease

GHO - Global Health Observatory

GLOBOCAN - estimated cancer incidence mortality and prevalence worldwide

HUI3 – a standardized instrument used as a measure of eight dimensions of health-related quality of life developed by Health Utilities Inc.

IAEA – International Atomic Energy Agency

IARC – International Agency for Research on Cancer

ICD-10 - 10th revision of the International Statistical Classification of Diseases and Related Health Problems

ICER – incremental cost-effectiveness ratio (the ratio of the difference in costs to the difference in benefits between two interventions)

LE – life expectancy

LR – lifetime risk

PAF/PAR – population attributable fraction/population attributable risk

QALYs – quality-adjusted life years

RR – relative risk

SE – standard error

TASL – Track Analysis Systems Limited

WHO – World Health Organisation

WLM – working level month, a cumulative exposure defined as breathing a concentration of 1 WL (2.08 x 10^{-5} J/m^3) for a working month of 170 hours. (1 WLM = 6.37 x 10^5 Bq/m3 per hour for equilibrium equivalent concentration of radon. Assuming equilibrium factor of 0.4 and 7000 hours per year indoors at home, 1 Bq/m3 radon exposure for 1 year = 0.0044 WLM at home.)

Abstract

Background: Lung cancer was the fifth leading cause of mortality globally in 2010, and the leading cause of cancer mortality in Canada, representing 26% of all cancer deaths for both men and women in 2017. Radon is a very modifiable environmental exposure that is the second most important cause of lung cancer.

Objectives: The objectives of this thesis are to quantify the lung cancer burden associated with residential radon and to identify the most cost effective mitigation options to reduce residential radon in Canada.

Methods: The global burden of lung cancer mortality attributable to radon in 2012 was estimated from the 66 countries for which a representative national radon survey was available, using several different models for excess relative risk (ERR) of lung cancer from radon studies. Cost-utility analyses are conducted for 20 practical radon interventions scenarios to reduce residential radon exposures in new and existing housing in Canada, each province/territory and 17 census metropolitan areas. A societal perspective and a lifetime horizon are adopted. A Markov cohort model and a discrete event simulation are used to model residents by household, based on a period-life table analysis, at a discount rate of 1.5%.

Results: The estimates of the global median PAR were consistent, ranging from 16.5% to 13.6% for the three ERR models based on miners, and the mean estimates of PAR for Canada ranged from 16.3% to 14.6%. It is very cost effective to install radon preventive measures in new construction compared to no radon control in all regions across Canada. At a radon mitigation threshold of 100 Bq/m^3, the sequential analysis recommends the combination of the activation of preventive measures in new housing with the mitigation of existing housing at current testing and mitigation rates for cost effectiveness thresholds between 51,889 and 92,072 \$/QALY for Canada, between 27,558 and 85,965 \$/QALY for Manitoba, and between 15,801 and 36,547 \$/QALY for the Yukon. The discounted ICER for screening and mitigation of existing housing at current rates relative to no radon control measures is 62,451 (66,421) \$/QALY using a Markov cohort model (discrete event simulation model) for mitigation of housing above a threshold of 200 Bq/m^3, and is 58,866 (59,556) $/QALY using a Markov cohort model (discrete event simulation model) for mitigation of housing above a threshold of 100 Bq/m^3.

Conclusions: Cost effective residential radon interventions should be implemented across Canada to reduce exposures to this very modifiable cause of lung cancer and to help reduce the increasing lung cancer burden in an ageing Canadian population.

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Chapter 1 – Introduction

1.1 Introduction

Residential radon is a causal factor for lung cancer, second only to smoking, and it constitutes an environmental exposure that can be reduced or prevented by public health measures. The health burden from radon associated lung cancer includes lung cancer morbidity and mortality, and the reduced quality of life following a diagnosis of lung cancer.

Lung cancer is an important cause of morbidity and mortality in the Canadian population; it constitutes 14% of all cancer incidence in men and women, and 26% of all cancer deaths in men and women (Canadian Cancer Statistics Advisory Committee 2018). Recently, it was estimated that 16% of lung cancer deaths in Canada were attributable to residential radon (Chen et al. 2012). Morbidity is also significant for lung cancer in Canada, with the 5 year survival rate reported to be 17% and the 10 year survival rate to be 13% (Canadian Cancer Society et al. 2014).

Assessment of the public health impact resulting from residential radon exposures constitutes the first step in the development of practical and coherent health policies to reduce radon exposures and the associated lung cancer burden. Following identification of significant adverse effects from residential radon in a specific population, the cost-utility of practical interventions to reduce radon can be evaluated. Measures used to control risks from residential radon include education, radon reduction in new construction and mitigation of existing housing screened and found to have radon above the mitigation threshold level. In countries such as Canada where the mitigation of radon in existing homes is voluntary, education campaigns aim to raise awareness of the risks of residential radon and to encourage home owners to conduct radon tests and mitigate when high radon levels are identified. Regulation has been introduced in high radon areas in Canada requiring preventive radon measures to be installed in new housing during construction.

1.2 Radon

Radon-222 is a colourless, odourless, radioactive gas that occurs naturally when the uranium-238 present in rock and soil undergoes radioactive decay. Most human exposure to ionizing radiation results from natural sources as shown in Figure 1: the highest proportion from natural radon at 42%, followed by 16% from external terrestrial sources, 13% from cosmic radiation, and 9% from ingested food and water. The most common iatrogenic source is medical diagnostics, contributing 20% of the average total dose of 3 mSv/year of radiation to which an individual is exposed in everyday life (Canada's Nuclear Safety Commission 2012).

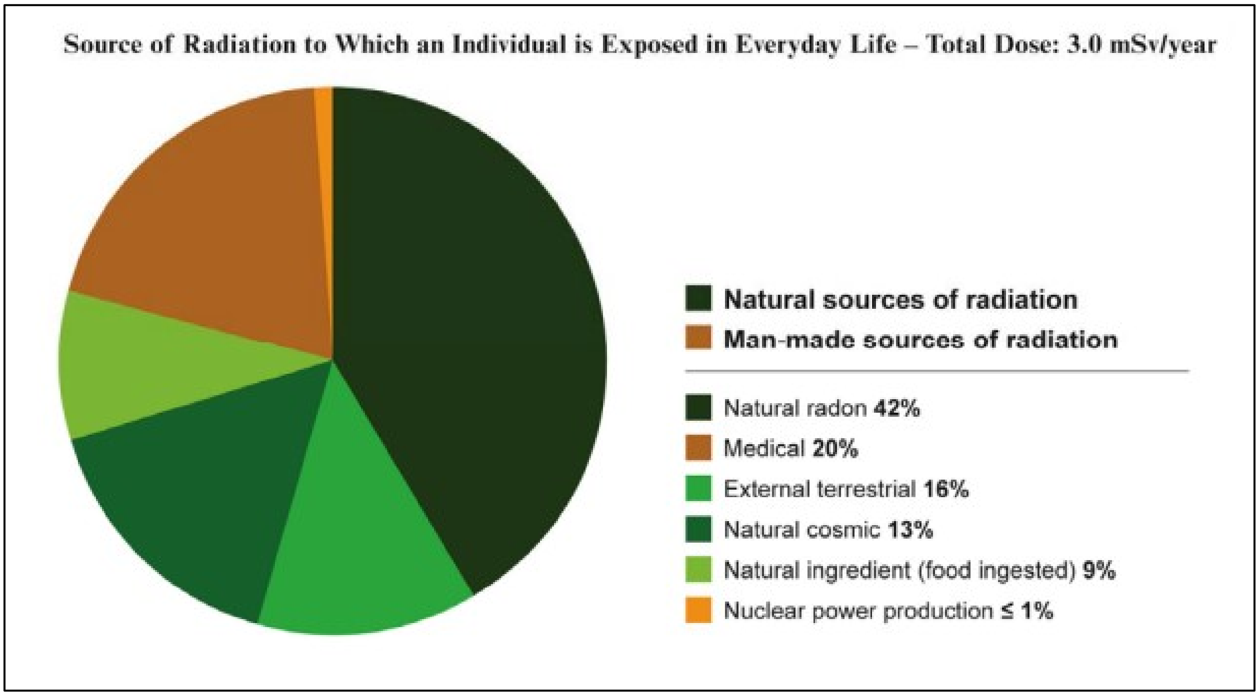

Figure 1: Common sources of exposure to radiation (Canada's Nuclear Safety Commission 2012)

Radon gas (radon-222) results from the decay of radium-226; the decay path of radon and radon progeny is shown in Figure 2. Radon-222 has a half-life of 3.8 days and emits alpha and beta particles until the decay path reaches lead-210, a relatively stable isotope that has a half-life of 22 years. An alpha particle is a helium 2+ ion consisting of two neutrons and two protons, and alpha radiation is characterized by high linear energy transfer and low penetrance (less than 80 µm for alpha radiation) (ATSDR 1999)). The adverse effects of radon result primarily from exposure of the lung to alpha radiation after inhalation of radon progeny. Radon can accumulate in poorly ventilated indoor areas, forming in soil and rock surrounding the foundations and seeping through cracks in foundations, walls and floors.

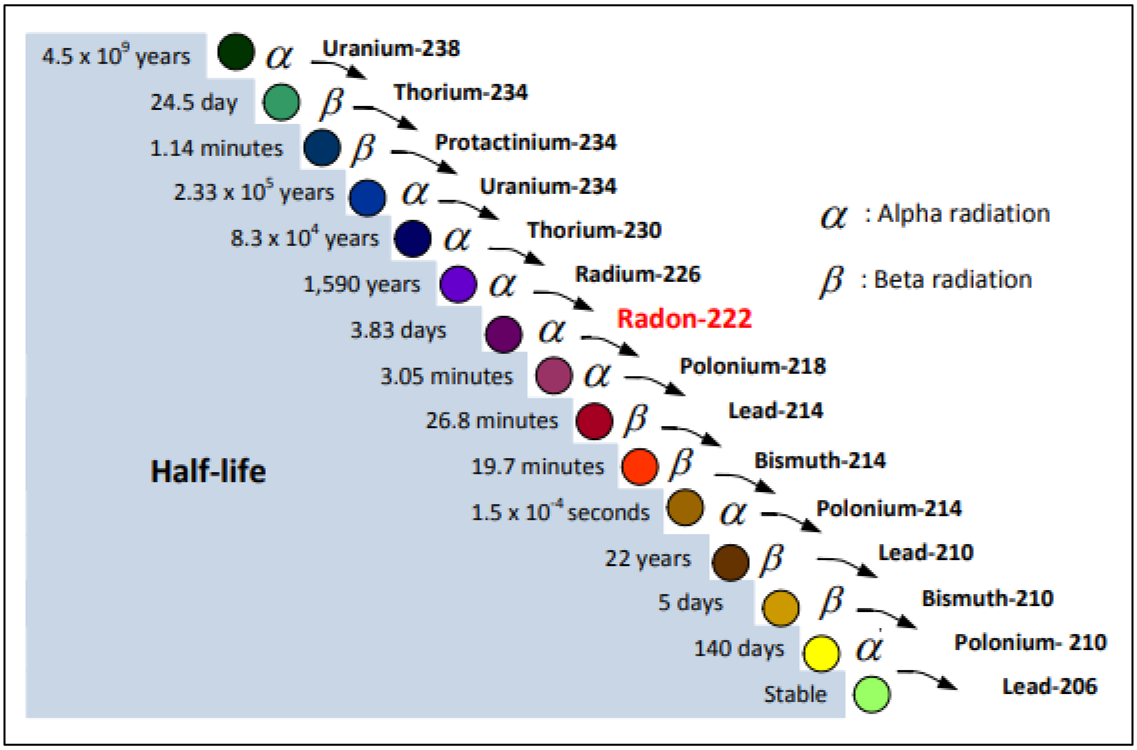

Figure 2: Decay path of radon and radon progeny (Canada's Nuclear Safety Commission 2012)

1.3 Biological effects of radon exposure

Exposure to radon, measured in Becquerels per meter cubed (Bq/m^3) is related to effective dose (mSv) using the dose conversion convention on the basis of equal detriment; detriment is a concept that reflects the adverse health effects experienced by an exposed group and their descendants (Tirmarche et al. 2010). Ionizing radiation from residential radon is delivered mostly to target tissues in the respiratory tract from short-lived radon progeny particle clusters, which grow to about 1 nm in diameter and may attach to existing aerosol particles within 1-100 seconds. Most of the inhaled radon gas that is inhaled is subsequently exhaled, with no increase in radiation due to the 3.8 day half-life of radon gas. However, breathing rate is a factor that influences the inhalation and deposition of particles in the lungs. Particles clusters deposited in the lungs are cleared either by absorption into the bloodstream or transport into the alimentary tract. Most of the dose from particle clusters deposited in the lungs is delivered to the cells in the bronchial and bronchiolar regions of the lung tissue, due the short half-lives of radon progeny, before the particle clusters are cleared either by absorption into the bloodstream or transport into the alimentary tract. Relatively little of the dose from particle clusters is delivered to the alveolar region (Tirmarche et al. 2010).

Radiation can cause cancer via direct alterations to DNA or indirect oxidative modifications of DNA (Alavanja 2002) caused by reactive oxygen species. Tissue damage from low dose alpha radiation is due to a small number of densely ionizing tracks delivering a large localized energy. Genetic lesions that have been associated with alpha radiation include double-strand chromosomal breaks, point mutations and translocations, induction of micronuclei, and sister chromatid exchange (SCE). This is coherent with the strong and significant association reported in a study of radon-exposed miners between incidence of lung cancer and frequency of chromatid breaks and aberrant cells, which were significantly correlated with radon exposure but not with smoking (Smerhovsky et al. 2002).

Reactive oxygen species (ROS) are generated by ionizing radiation deposited in cells, with about 80% of the energy released when electrons are ejected from water molecules in the cell, resulting in the hydroxyl radical, which is the most damaging ROS (Riley 1994). Hydroxyl radicals can damage DNA directly or indirectly by reacting with oxygen to create other ROS such as superoxides that can damage DNA. Damage caused by hydroxyl radicals includes DNA alterations, decreased enzyme activity, advanced glycation end products (AGEs), and lipid peroxidation, which allows leakage of enzymes, electrolytes, transition metals and small molecules when lipids in the lipid membrane are damaged (Jomova and Valko 2011). Increased formation of proinflammatory cytokines, such as interleukin-6 (IL6), results from the activation of signaling pathways by receptors for AGEs (RAGEs). Another ROS resulting from ionizing radiation is hydrogen peroxide, which persists due to its relative stability and causes similar cellular damage (Alavanja 2002). ROS can induce mitosis in cells in addition to damaging DNA. Initiation and/or tumour progression can result if the induced cell division involves mutated oncogenes or suppressor genes (Loft and Poulsen 1996). ROS, therefore, may promote multiple stages in carcinogenesis.

In radon inhalation studies, carcinogenesis depends on the dose and on the sensitivity of the cell to radiation. Most respiratory tract epithelial cells have long cell-turnover times, with little of that time spent in radiation sensitive stages. The dose to individual cells in the respiratory tract is calculated from the number of traverses, the distance from the airway surface, and the thickness of the mucus on the airway. The number of alpha particle hits for lung cells in different target locations, calculated for different cumulative exposures, showed that bronchial and bronchiolar secretory cell cytoplasm receive the greatest number, which is consistent with tumours being most common in the bronchi and bronchioles (EPA 2011).

Many steps are involved in the development of a tumour, often from a single mutated cell. Experiments by Hei et al (1994) have shown that a single small dose of alpha particles, averaging a few particles per cell nucleus, can cause broncoepithelial cells to become tumorigenic. Tissue response and immunologic factors mediate progressive stages, described as initiation, promotion, and progression. The degree of oxidative stress can be mediated by the reducing potential or antioxidant capacity of the cell, including the glutathione-related and peroxiredoxin (Prx) systems. Meta-analyses of studies of the effect of polymorphisms of glutathione-S-transferase M1 (GSTM1) and lung cancer risks have not been consistent (Carlsten et al. 2008; Liu et al. 2015; Yu et al. 2018). However, a recent and very large meta-analysis based on a total of 40,296 cases and 48,346 controls reported that the GSTM1 null polymorphism was reported to be associated with an elevated risk of lung cancer, while the present polymorphism provided a protective effect (Yu et al. 2018). This study also reported that air pollution and smoking were effect modifiers having an additive effect on the association between the GSTM1 null polymorphism and lung cancer risk, with risks increasing for smokers having higher air pollution exposures. Oncogenes and suppressor genes are also important in tumourigenesis. Mutations in the suppressor gene TP53 that encodes the p53 protein are common, detectable in up to 50% of NSCLC and in over 70% of SCLC (IARC 2004).

1.4 History of Radon Associated Lung Cancer

Silver mining started at the northern slopes of the ore mountains ("Erzgebirge") in the Schneeberg region of Germany about 1470. Lung disease having an usually high mortality rate was first reported to be frequent in younger miners by Paracelsus (1493-1541) and became known as Schneeberg lung disease in the 17^{th} and 18^{th} centuries. It was identified as lung cancer in 1879 by Haerting and Hesse (Jacobi 1993), who reported that about 75% of the Schneeberg miners died of lung cancer.

Extensive uranium mining for military purposes started during World War II, primarily in the Congo, Canada, the US, Germany (Schneeberg) and the Czech Republic (Jachymov). Quantitative studies of the risk of lung cancer from inhaled radon progeny were first determined for cohort of uranium miner in the US, Canada, Germany, Czechoslovakia, France and Australia with recruitment starting in the 1940s and 1950s. The analyses used a linear dose-response model for cohorts (having a follow-up of roughly twenty years and assuming an exposure lag time of 5 years) with good documentation of age at exposure and time since exposure, although not of smoking habits. Lubin et al. (1995a) reported an exposure-response trend for never-smokers three times that for smokers, though the relative risk of lung cancer was found to increase with increasing cumulative radon exposure for both smokers and nonsmokers. The mean excess relative risk per 100 Working Level Months (WLM) calculated from the seven cohort studies considered in the 1993 ICRP Publication 65 was 1.34 (95% CI: 0.82, 2.13), calculated from the eleven cohort studies considered in the 1999 BEIR VI report was 0.59 (SE 1.32), and calculated from the nine cohort studies considered in the 2009 UNSCEAR report was 0.59 (95% CI: 0.35, 1.0) (Tirmarche et al. 2010).

The risk of lung cancer in the general public from residential radon exposures was assessed after studies of miners showed that exposure at lower doses was harmful to human health. An inverse dose-rate effect was reported in the analysis of pooled data from 11 cohort studies of radon-exposed miners reviewed by Lubin et al (1995b), although it diminished to zero for cumulative radon exposures below 50 WLM, suggesting that a linear dose-response model was appropriate for the lower residential exposures. Restriction of studies to cohorts of miners with cumulative radon exposures below 50 WLM yielded an estimate of the ERR per 100 WLM of 1.17 in the BEIR VI report (BEIR VI Report 1999).

Alpha particles, like other densely ionizing radiation, exhibit an inverse dose-rate effect for carcinogenesis, but exhibit a linear dose response relationship at low doses and low dose rates. An inverse dose-rate effect was reported in the analysis of pooled data from 11 cohort studies of radon-exposed miners (Lubin et al. 1995a); exposure at lower doses were more harmful than those at higher doses for a given cumulative exposure. Biological mechanisms that could explain the interplay of exposure and exposure rate include high dose-rate saturation (when multiple traversals occur during a sensitive stage of the cell cycle), killing of initiated cells, and an enhancement of cellular repair. Increased effect at low dose rate could result from enhancement of cellular proliferation, misrepair or transformation processes. At cumulative exposures resulting from low-dose indoor exposures (characterized by low probability of multiple alpha particle traversals), the effect varies directly with dose rate.

Other lung carcinogens include tobacco smoke, arsenic, and asbestos, to which miners can also be exposed. Most of the carcinogens in tobacco smoke are found in the particulate phase. Oxidative stress induced by reactive oxygen species is the biological mechanism common to both radon and carcinogens in tobacco smoke particulates, resulting in lipid peroxidation and an increase in a marker of oxidative damage to DNA known as 8-hydroxy-deoxyguanosinen peroxide (Alavanja 2002; Loft and Poulsen 1996). Higher doses of alpha radiation to the lung result when tobacco smoke is present, due to the inhalation of greater numbers of attached radon progeny, because tobacco smoke increases the concentration of particles to which radon progeny become attached (Abdel-Ghany 2007; Tirmarche et al. 2010). Lung morphology studies do, however, suggest a decreased risk of radiation dose for moderate smokers due to mucous coating the respiratory tract epithelium. Biological and physical mechanisms support the increased association between residential radon and risk of lung cancer reported for nonsmokers exposed to environmental tobacco smoke.

Residential cohorts of radon exposure have enabled the evaluation of the relative risk for a broader population, including women and children, and the documentation of important confounders, in particular tobacco smoke. Eighteen case-control studies and one cohort study of residential radon exposure (having more than 200 cases of lung cancer) were published between 1990 and 2006, but were found to have low statistical power and yielded wide confidence intervals when considered individually (Tirmarche et al. 2010). Very large sample sizes are required for the evaluation of the small causal effects that are common for environmental exposures. Three high-quality joint analyses have been published that included more than 400 non-smoking cases of lung cancer, had radon exposure assessment from alpha-track detectors covering most long-term residences between 5 years and 30 or 35 years prior to lung cancer diagnosis (the exposure time window or ETW), and used standardized protocols for thorough assessment of potential confounders. Adjustment for attained age, sex, study, smoking factors, residential mobility, and completeness of radon measurements showed that the odds ratio of lung cancer generally increased with radon concentration and was consistent with linearity. The excess relative risk per 100 Bq/m^3 determined from the joint analysis of data for Europe was ERR=0.08 [5% CI: 0.03-0.16], for North American was EOR=0.10 [95% CI: -0.01, 0.26], and for China was EOR=0.13 [95% CI: 0.01-0.36] (Lubin 2003)(Darby et al. 2006a; Krewski et al. 2006; Lubin 2003).

Pooled residential case-control study results have demonstrated that failure to account for the effect of smoking on lung cancer tends to bias the risk from radon exposure towards the null because smoking and residential radon exposure tend to be negatively correlated (Tirmarche et al. 2010). The relative risk of lung cancer was 1.02 per 100 Bq/m3 radon, stratified for covariates except smoking status (study, region, age and sex), and increased to 1.08 for the most extensive stratification of smoking status and history. However, pooled residential studies have not reported any significant heterogeneity in excess odds ratio according to smoking status (Darby et al. 2006a; Krewski et al. 2006). Analysis of lung cancer incidence among atomic bomb survivors revealed that models assuming generalized interactions between smoking and radiation gave a much better fit than simple additive or multiplicative models (Furukawa, Kyoji et al. 2010): for light to moderate smokers the joint effect appeared to be super-multiplicative, whereas for heavy smokers (smoking a pack a day or more) the joint effect was additive or sub-additive.

Lung cancer deaths constitute the majority of cancer deaths, and the two most important risk factors are tobacco smoke and residential radon (WHO 2009). Smoking is such a strong risk factor that estimating the effect size of other risk factors, such as radon or ambient air pollution, relies on thorough adjustment for confounding from smoking. Nonsmokers have, therefore, been identified as the ideal subgroup in which to study risk factors for lung cancer other than smoking (such as radon). Until recently, lung cancer in nonsmokers has been considered less relevant for public health. Consistent estimates of the risk of lung cancer in nonsmokers have been determined using the most accurate and precise residential radon exposures in the three pooled case-control studies having more than 400 cases of lung cancer in nonsmokers with adjustment for environmental tobacco smoke: EOR=0.22 (Krewski et al. 2006), ERR=0.20 [0.02 – 0.52] (Darby et al. 2006a), and ERR=0.28 [-0.05 – 1.05] (Lagarde et al. 2001).

Pollutants emitted by industrial activity and transportation, including diesel exhaust, are sources of particulate air pollution and nitrogen dioxide that would be possible confounding variables between residential radon exposure and lung cancer for outdoor and indoor exposures because the fine soot, or PM 2.5 is detected in indoor as well as outdoor air (Cui et al. 2015; Hamra et al. 2014, 2015; Sun et al. 2014). It would be expected that PM 2.5 levels in indoor air would be higher for housing that is close to major roads and routes used by buses and trucks, and higher for apartments on upper floors than in houses, and therefore possibly inversely correlated with radon exposure. Evans et al. (2013) estimated that attributable global fraction of adult lung cancer mortality from PM 2.5 was 12.8%. Arsenic in drinking water could be a confounder for households that use groundwater, which is the source of municipal water in many rural communities in addition to houses that have wells (Field and Withers 2012), and therefore possibly correlated with radon exposure because there are more houses and fewer tall apartments in rural compared to urban areas. Asbestos is another cause of lung cancer, but unlikely to be a confounder for the association of residential radon and lung cancer because any asbestos used as insulation in homes is not considered a risk factor unless the walls are demolished in a home renovation conducted by home owners who are unaware either of the existence of asbestos or the associated risks from asbestos exposure. Other lung cancer causes to which underground miners can be exposed to, such as arsenic, diesel exhaust, silica dust or occupational exposure to certain chemicals, are unlikely to be confounders for residential radon exposure and lung cancer, because any occupational exposures would not be expected to be associated with residential radon exposures. In a more global setting, any indoor air pollutants including open coal fires in Asia and biomass fires used for heating and cooking in many continents have been associated with increased excess odds ratio of lung cancer (Hosgood et al. 2010; Kurmi et al. 2012) and could be inversely associated with residential radon exposures due to increased natural ventilation where open coal or biomass fires are used indoors.

1.5 Residential Radon Exposure Assessment

In order for a residential radon measurement to be representative of the average indoor radon exposure, it is recommended that it consist of an integrated measurement recorded over a extended time period (International Atomic Energy Agency 2013; World Health Organization 2009). This time period should be at least 3 months long, due to the very large diurnal and seasonal variations in indoor radon levels that have been recorded. In cold climates, radon levels are highest in the winter when ventilation rates are lowest, and it is recommended in Canada that residential radon be measured for at least 3 months during the winter (Health Canada 2017).

Occupational exposure to radiation is measured using a personal dosimeter, a small device worn on the torso or the finger of the person that contains a substance sensitive to radiation that can quantify and record the dose being received. However, the dosimeter is not sensitive to the type of radiation, whether gamma, beta or alpha. The majority of occupational exposure in Canada in 2017 occurred among medical personnel (57%) and the most common dosimeter is only sensitive to beta and gamma radiation (Health Canada 2018). Occupational exposure to alpha radiation is less common, occurring mostly among miners (3%) and nuclear power workers (16%). These workers must wear a specific dosimeter that is sensitive to alpha radiation, usually in addition to the standard dosimeter that is sensitive to beta and gamma radiation, in order to measure total occupational exposure. Most dosimeters do not give real time measurements; the occupational exposure is monitored by having the dosimeter read every two weeks or every month in order to determine the total dose since the previous dosimeter assessment. In rare cases, such as emergencies at nuclear power plants, electronic personal dosimeters are now available that can display the dose rate and cumulative dose and give alerts when dose limits are exceeded.

It is impossible to estimate residential radon exposures because it is an invisible and odourless gas, and the levels in one house can be very different from the neighbouring house. Therefore, only measurements are used to assess radon, never questionnaires. Passive devices have been extensively used because they are very reliable whereas as active devices require electric power to record fluctuations in concentration over the measurement period (International Atomic Energy Agency 2013; World Health Organization 2009). Passive radon detectors include alpha track detectors, and the electret ion chamber, which is more expensive and is sensitive to background gamma radiation. Active radon detectors include the electronic integrating devices, which are sensitive to humidity, and continuous radon monitors, which require routine calibration for reliable results, but active radon detectors are too expensive to use for large radon surveys (International Atomic Energy Agency 2013; World Health Organization 2009).

The alpha track detector is considered the gold standard for large residential radon surveys because it is very reliable and affordable for long term measurements and it is a passive device that is not sensitive to background radiation, temperature or humidity (International Atomic Energy Agency 2013). Alpha track detector are small units about the size of a hockey puck that contain a plastic substrate within a diffusion chamber that only radon and no progeny can enter. When the radon decays, the alpha particle etches the plastic, and at the end of the measurement period, the detector is sent back to the laboratory where the number of etchings per unit area are counted and from which the average radon concentration is determined. Alpha track detectors also produce a permanent quality record that can be re-analyzed in the future. Two long term radon detectors are recommended in Canada, the alpha track detector and the electret ion chamber (Health Canada 2017).

1.6 Radon Control

Revisions made in 2010 to the National Building Code (NBC) of Canada for radon control in new homes included a rough-in requirement for a future radon removal system, the use of a vapour barrier under the foundation slab, and sealing sump pits, cracks and joints in the foundation floor and walls. The recommended guideline for acceptable level of residential radon is currently 200 Bq/m^3. However, the NBC recommendations have yet to be adopted into all provincial codes, which are the legally binding codes.

Chronic disease in a population is described by a continuous distribution, and the use of cutoffs to identify those at highest risk (who will receive an intervention) is arbitrary. Dr. Geoffrey Rose promoted the implementation of broad public health measures for common diseases or exposures. Reducing the smaller risks experienced by the middle of the distribution will prevent a far greater number of cases of a disease than adopting a high risk preventive strategy, which is limited to a “targeted rescue operation for vulnerable individuals” at the tail of the distribution (Rose 2008). It was estimated that 73% of lung cancer deaths attributable to residential radon in Ontario (Peterson et al. 2013) and 85% in the UK (Gray et al. 2009) would result from exposures below 100 Bq/m^3.

Radon prevention measures applied to all new construction reduce all radon exposures in the distribution and are the intervention with the lowest cost. Mitigation of existing housing is restricted to those with radon above a mitigation threshold, because the cost of mitigation is significantly higher than that for prevention. The installation of passive preventive measures during construction typically yield about a 50% reduction in radon levels, reported in a study in Devon and Cornwall in the UK that compared radon levels in new housing with and without radon membranes (Woolliscroft et al. 1994). Studies of the reduction in radon in houses after installation of active depressurization systems in Denmark and in Canada reported reductions of 85% (Andersen et al. 1997) and 91% (Health Canada 2016), respectively. The combination of practical radon interventions that will be considered cost effective from a societal perspective for a population depends on radon exposures, housing characteristics and societal factors such as smoking rates and overall and lung cancer mortality rates.

1.7 Residential Radon Remediation: A Health Intervention in Canada

Remediation of residential radon exposure constitutes a health protection intervention because the health care system is responsible for the costs of lung cancer treatment. The average annual costs of lung cancer care in Canada were estimated to be 7.5 billion dollars (adjusted to 2015 Canadian dollars) in 2012 (de Oliveira et al. 2018). Sixteen percent of lung cancer mortality in Canada was recently attributed to residential radon exposure (Chen et al. 2012). It would be beneficial for decision makers, who must balance investment in lung cancer prevention with treatment programs, to have estimates of the incremental cost effectiveness ratio of practical radon interventions in Canada and for each province and territory. Relevant decision makers might include the provincial health authorities, the provincial housing authorities (regarding the provincial building codes), municipal housing authorities who enforce building codes and issue permits, and several federal departments.

1.8 Research Objectives

Two main approaches are used in this thesis to address the burden of lung cancer associated with residential radon: A) a burden of disease approach assuming complete or uniform reduction of residential radon, globally and in Canada, and B) a health economic analysis assessing the utility, cost and cost effectiveness of realistically attainable reductions in radon exposures across Canada:

A. Burden of lung cancer associated with residential radon
   1. Determine global burden of lung cancer attributed to residential radon
   2. Determine the modifiable burden of lung cancer associated with residential radon remediation in Canada, the provinces/territories, and 17 CMAs

B. Economic evaluation of practical interventions to reduce residential radon in Canada
   3. Conduct a cost-utility analysis of radon intervention scenarios to reduce residential radon in Canada, the provinces/territories, and 17 CMAs, relative to passive preventive measures installed in new housing

4. Estimate the cost-effectiveness of radon interventions for mitigating existing housing in Canada relative to no radon control measures and to assess the structural uncertainty associated with the model structure

Chapter 2 estimates the global burden of lung cancer mortality from evaluation of the population attributable risk for each of the 66 countries for which a representative radon survey has been conducted. The health burden in Canada from lung cancer mortality attributed to radon was assessed by the population attributable risk and the attributable number of lung cancer deaths. Chapter 3 estimates the modifiable burden of lung cancer associated with residential radon exposures in Canada, the provinces and territories, and 17 census metropolitan areas. The modifiable burden was calculated from the theoretical application of two residential radon control techniques used in new housing, corresponding to a 50% reduction and an 85% reduction in radon, to the entire housing stock.

Chapter 4 describes the use of economic health evaluations in Canada and the current regulatory framework for radon that exists across Canada. Chapter 5 estimates the incremental cost-utility ratios for practical interventions, from a baseline scenario of passive preventive measures installed in new housing at construction to scenarios that also include more comprehensive radon mitigation in existing housing, to reduce population residential radon exposures in Canada, the provinces and territories, and 17 census metropolitan areas using a Markov cohort model. Chapter 6 estimates the incremental cost-effectiveness of mitigating radon in existing housing only for Canada and assesses the structural uncertainty associated with the model structure selected. A discussion of the results and of the implications for policies concerning radon control in Canada concludes the thesis in Chapter 7.

The analyses conducted in the thesis include assumptions in the models used to characterize the radon exposures of populations and evaluate the costs and benefits of specific interventions to reduce those radon exposures. It is assumed that representative distributions for the radon exposure of the national populations in the global analysis were reported from radon surveys that were based on the measurement of radon concentrations in a randomly selected sample of at least a few thousand housing units, usually based on 3 to 12 month-long measurement using alpha-track detectors. High quality representative radon surveys were used to determine distributions for radon exposures for the national, provincial/territorial and municipal populations in Canada. All of the analyses rely on published models of excess relative risk of lung cancer mortality attributable to radon exposure to characterize the population risk from radon exposures to residential radon and to calculate the decrease in risk that results from reducing the residential radon exposures. Five different excess relative risk models were used for objective A1, and the BEIR VI exposure-age-concentration model for radon attributable lung cancer mortality was used in all analyses in this thesis. An individual's age-specific risk of lung cancer attributable to radon can be calculated from estimating the cumulative radon exposure that results from their past exposure to radon, at each age over their life span, using the BEIR VI exposure-age-concentration model.

The analyses for Canada model populations based on the assumption that the populations are represented using categories for age, sex, and smoking status. The modifiable burden of lung cancer is that associated with the maximum theoretical reduction in residential radon in Canada because residential radon can be reduced but not completely eliminated by the radon interventions used in housing. The cost-utility analyses use a housing model to estimate what proportion of the housing stock is new housing that has passive preventive measures installed and radon exposures reduced by 50%, what proportion of housing has no radon control measures and current radon exposures, and what proportion of housing has active depressurization system and radon exposures reduced by 85%, and tracks the timing of changes in these proportions for each five year period over the hundred year time horizon. The analyses assume that the implementation of the radon remediation measures are as effective in housing at the population scale as they were estimated to be from field studies conducted by researchers. The costs of radon remediation measures were assumed to remain constant through the hundred year time horizon, though this is expected to be conservative because as radon mitigation becomes more common the costs would be expected to decrease.

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Chapter 2 - Global Estimate of Lung Cancer Mortality Attributable to Residential Radon

2.1 Abstract

Background Radon is the second most important cause of lung cancer, ranked by the World Health Organisation as the fifth leading cause of mortality in 2010. An updated database of national radon exposures for 66 countries allows the global burden of lung cancer mortality attributable to radon to be estimated.

Objective Our goal was to estimate the global population attributable burden of lung cancer mortality in 2012 from residential radon.

Methods Estimates of the population attributable risk (PAR) of lung cancer mortality from radon were determined using the attributable fraction approach, using three models for excess relative risk of lung cancer from radon.

Results The estimates of the median PAR of lung cancer mortality from residential radon in 2012 for the 66 countries having representative national radon surveys were consistent, as 16.5%, 14.4% and 13.6% for the exposure-age-concentration (EAC) model (BEIR VI), the Hunter model and the Kreuzer model, respectively. The mean PAR using the EAC model ranged from 4.2% (95% CI: 0.9, 11.7) for Japan, to 29.3% (95% CI: 22.9, 35.7) for Armenia, with a median for the 66 countries of 16.5%. Radon attributable lung cancer deaths for all 66 countries totalled 226,057 in 2012 and represent a median of 3.0% of totaled cancer deaths.

Conclusions Consistent findings between the three models used to estimate excess relative risks of lung cancer from radon, and between the attributable fraction methodology and the life table analysis, confirm that residential radon is responsible for a substantial proportion of lung cancer mortality worldwide.

2.2 Introduction

Radon is the second most important cause of lung cancer, after smoking (Zeeb 2006). Radon-222 and its decay products were classified as a known cause of human cancer by the International Agency for Research on Cancer (IARC) in 1988 (IARC 2012 Volume 100D). Radon-222 is a colourless, odourless, radioactive gas that occurs naturally when the uranium-238 present in rock and soil undergoes radioactive decay. The short-lived radon progeny (or decay products) are also radioactive. The alpha radiation emitted by radon progeny inhaled into the lungs can damage cellular DNA, which can eventually result in clinically evident lung cancer. Radon can accumulate in poorly ventilated buildings, especially in basements, when radon from the ground seeps in through entry points such as cracks in the foundations.

Strong and complementary evidence of the risks of lung cancer from cumulative exposure to radon and its progeny via inhalation have been determined from studies of occupational exposures of uranium miners and residential exposures of the public (Tirmarche et al. 2010). An inverse dose-rate effect was reported in the analysis of pooled data from 11 cohort studies of radon-exposed miners reviewed by Lubin et al. (1995). The risk to miners exposed at lower doses initiated studies of the risk to the general public from residential radon. Evaluation of the lower residential radon exposures of the pooled case-control studies yielded results consistent with those from the miner studies, and showed that the odds ratio of lung cancer generally increased with radon concentration and was consistent with linearity. After adjustments for uncertainties in radon measurements, the excess risk ratio (ERR) was 0.16 (95% confidence interval (CI): 0.05-0.31) for European pooling (Darby et al. 2006b) and the excess odds ratio (EOR) was 0.18 (95% CI: 0.02, 0.43) per 100 Bq/m^3 for North American pooling (Krewski et al. 2006). Recent estimates of excess rate ratio(ERR/WLM) were derived from studies of miners having low radon exposure rates and low cumulative exposures similar to those from residential radon: ERR/WLM = 0.017 (95% CI: 0.009, 0.0035) from three European nested case-control miner studies restricted to cumulative exposures <300 WLM (Hunter et al. 2013); and ERR/WLM = 0.013 (95% CI: 0.009, 0.0035) from a German miner cohort with mean cumulative exposure of 17 WLM (range: 0-334 WLM) (Kreuzer et al. 2015).

The global burden from lung cancer mortality is significant and steadily increasing. The World Health Organization (WHO) Global Burden of Disease (GBD) reported that trachea, bronchus and lung cancers represented 19% of all cancer deaths and ranked as the fifth leading cause of death worldwide (Lozano et al. 2012). Although the age-standardized lung cancer mortality rate decreased by 9%, the number of lung cancer deaths increased by 57% between 1990 and 2013, primarily due to the aging of the population in low and middle income countries (Naghavi et al. 2015). The goal of this research was to compare estimates of the number, the percentage of total cancer deaths, and the population attributable risk (PAR) for lung cancer mortality in 2012 due to residential radon using an updated global radon database.

2.3 METHODS

2.3.1 Study Design

The global burden of lung cancer mortality attributed to residential radon was estimated for the 66 countries that have conducted a representative national radon survey. The lung cancer mortality attributable to radon was estimated from the attributable fraction approach, using three different models to calculate the excess rate ratio from radon: the BEIR VI exposure-age-concentration (EAC) model (NRC 1999), the Hunter et al. (2013) model, and the Kreuzer et al. (2015) model. Estimates of the mean and 95% confidence intervals were determined for the population attributable risk and the number of lung cancer deaths attributable to radon, with the uncertainty assessed using Monte Carlo simulation with 10,000 replications to sample the national distributions for residential radon and adult smoking prevalence for men and women and probabilistic distributions for the excess rate ratio models.

2.3.2 National assessment of lung cancer mortality attributed to residential radon

2.3.2.1 National Radon Exposure

The International Atomic Energy Agency (IAEA) has summarized the methodology and measurement techniques suitable for indoor radon surveys that are representative of a national or regional population (IAEA 2013). An estimate of either arithmetic or geometric mean national residential radon exposure was included in the updated database if it resulted from a systematic survey using a reliable radon measurement technique. The Medline database was searched on May 20th, 2017, using MeSH terms and keywords "Radon Daughters/ or Radon/" and "residential.mp.", published between 2000 and 2017. Of the 1599 papers identified, 27 were used to update the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2000 and 2006 databases (original sources referenced when provided). Radon distributions for the 66 countries included in the analysis are shown in Table 1 and the references listed in Appendix A Table S1. The lognormal distribution [defined by the geometric mean (GM) and standard deviation (GSD)] characterizing the residential radon for each country is sampled in the Monte Carlo simulation to provide a probabilistic estimate of the mean and 95% CIs of the lung cancer mortality attributable to radon. For the 22 countries with incomplete radon data, the geometric standard deviation was imputed from the mean based on linear regression of the data from countries reporting both a mean and GSD.

2.3.2.2 Lung Cancer Mortality by Smoking Status

National lung cancer mortality is reported at the detailed age- and sex-specific country-level WHO/IARC GLOBOCAN project for 2012: Estimated Cancer Incidence Mortality and Prevalence Worldwide (International Agency for Research on Cancer 2012). Statistical Classification of Diseases and Related Health Problems (ICD-10) for malignant neoplasm of bronchus and lung are C33-34. National smoking prevalence in 2012 amongst adult men and women, greater than 15 years of age, was obtained from the WHO Global Health Observatory data for prevalence of tobacco smoking (World Health Organization 2012) and is shown in Appendix A Table S2. The smoking prevalence for the nine countries missing adult data was imputed from similar countries using linear regression, and thus expected to contribute little to overall uncertainty. Lung cancer mortality was adjusted for smoking using the relative risk of lung cancer mortality for smoker versus nonsmokers and the adult smoking prevalence in each country (Tirmarche et al. 2010; Villeneuve and Mao 1994). The relative risk of lung cancer mortality for smokers versus nonsmokers (RR_e) by sex and age category reported by the American Cancer Society CPS-II (Thun et al. 1997) was used for all countries.

2.3.2.3 Excess Rate Ratio

Three different models are used to calculate the excess rate ratio from radon derived from the miner cohort studies because they are characterized by very good radon exposure assessment, annual measurements over long periods of occupational exposure. The BEIR VI EAC model is based on over one million person-years of observation, and the recent Hunter and Kreuzer models are based on low radon exposure rates and cumulative doses that approximate those resulting from lifetime residential exposures. The models used to calculate the excess rate ratio from radon include: a) the BEIR VI EAC model (NRC 1999) based on 11 miner cohorts, the most complete model that also fits low cumulative exposures; b) the model derived from three European nested case-control miner studies restricted to exposures less than 300 WLM (Hunter et al. 2013); and c) the model derived from a German miner cohort having low radon exposures rates, characterized by a mean cumulative exposure of 17 WLM, mean individual average radon exposure rate of 0.2 WL and mean duration of employment of 10 years (Kreuzer et al. 2015).

The ERR/WLM is 0.08 (GSD=1.36) for the BEIR VI EAC model, modified by factors for smoking status, effective exposure duration, exposure-rate effect, and attained age. Central estimates of the parameter values for the modifying factors were derived from an overall fit of the BEIR VI EAC model to 11 miner cohort studies taken from Krewski et al. (1999) as described in greater detail in Brand et al. (2005). For the Hunter et al. (2013) model restricted to <300 WLM, the ERR/WLM is 0.043 (95% CI: 0.022, 0.08) and 0.007 (95% CI: 0.002-0.018), for time since exposure of 5-25 years and greater than 25 years, respectively, and is also modified by a factor for attained age. The ERR/WLM is 0.013 (95% CI: 0.007, 0.021) for the unrestricted Kreuzer et al. (2015) model, based on cumulative radon exposures ranging from 0 to 334 WLM.

The three excess rate ratio models of lung cancer mortality used in this analysis are applied to lifetime radon exposure, assessed for each age-group in the population, assuming constant residential radon exposure and a 5 year latency period. The residential radon exposure in Bq/m^3 is converted into Working Level Months for use in the miner excess rate ratio models, assuming an equilibrium factor of 0.4 and 7000 hours per year indoors at home lead to 1 Bq/m^3 radon exposure for 1 year equalling 0.0044 WLM at home. The BEIR VI EAC model uses relative weights to progressively diminish the contribution of radon exposure greater than 15 years and greater than 25 years prior to lung cancer, and the Hunter et al. (2013) model reported a contribution at one-sixth for exposure greater than 25 years prior to the outcome (ERR/WLM=0.007 for exposure greater than 25 years prior). Although double the risk for nonsmokers than current smokers was reported in the Hunter model and a higher risk estimate for non/light smokers than for moderate/heavy smokers was reported in the Kreuzer model, neither model includes a factor for smoking status because the differences were not statistically significant.

Estimates of PAR are derived from the pooled residential studies (adjusted for uncertainties in radon measurement) by first converting each reported ERR to an excess rate ratio using cumulative radon exposure, ERR/WLM. The excess rate ratio for the residential studies was assumed to be contributed primarily from the period 5-25 years prior to lung cancer, with the model extended to lifetime exposure using the estimate reported by Hunter et al. (2013) for exposures greater than 25 years prior to lung cancer of ERR/WLM=0.007. The estimate for the period 5-25 years prior to lung cancer from the pooled North American study was ERR/WLM=0.018, based on of ERR=0.18 per 100 Bq/m^3 radon from Krewski et al. (2006), and from the pooled European study was ERR/WLM=0.014, based on ERR=0.16 per 100 Bq/m^3 radon from Darby et al. (2006).

2.3.2.4 Attributable Number and Risk of Lung Cancer Deaths

The excess rate ratio attributable to radon is calculated for each sex-age-smoking category and the attributable fraction is calculated using Equation 1:

$$AF = \frac{excess\ rate\ ratio}{1 + excess\ rate\ ratio} \qquad (Eq\ 1)$$

The attributable fraction is multiplied by the number of lung cancer deaths for each age-sex-smoking category to determine the number of radon attributable lung cancer deaths. For each country, the PAR of lung cancer mortality is given by the ratio of the sum of the attributable lung cancer deaths (over all age-sex-smoking categories) to the total number of lung cancer deaths.

2.3.3 Validation

The validity of the approach was assessed by comparing the results for Canada for radon PAR of lung cancer mortality from the attributable fraction approach to an alternative life-table analysis. The abridged period life-table approach will use 5 year age intervals, and age-and sex-specific all cause and lung cancer mortality rates will be calculated from the census and death database. The probabilities of death reported in the death database were first converted into mortality rates, so that an exposed person's risk can be modeled as the sum of the baseline risk and the risk due to radon exposure, expressed in terms of an intensity ratio. The excess rate ratio used to model the risk due to radon exposure in the life-table analysis is the BEIR VI EAC model described earlier. The probability of surviving to the beginning of each age interval, the probability of dying during the age interval, and the intensity ratio between all cause and lung cancer mortality are used to determine baseline and exposed life expectancy (LE, LE_E) and lifetime risk (LR, LR_E) of lung cancer. The population attributable risk (Equation 2) is calculated from the population-averaged lifetime risk in the exposed (LR_E) and the baseline lifetime risk for a theoretical unexposed population (LR) as described in Brand et al. (2005):

$$PAR = \frac{LR_E - LR}{LR_E} \qquad (Eq\ 2)$$

2.4 Results

The geometric means of the national residential radon distributions around the world are shown in Figure 3. The national residential radon distributions for the 66 countries around the world are listed in Table 1 and the national adult male and female smoking prevalence distributions in Appendix A Table S2. Geometric mean radon exposures for the 66 countries ranged from 133 Bq/m^3 for Poland to 5 Bq/m^3 for Cuba, with a median of 38 Bq/m^3. The median adult smoking prevalence was 35% for males and 18% for females.

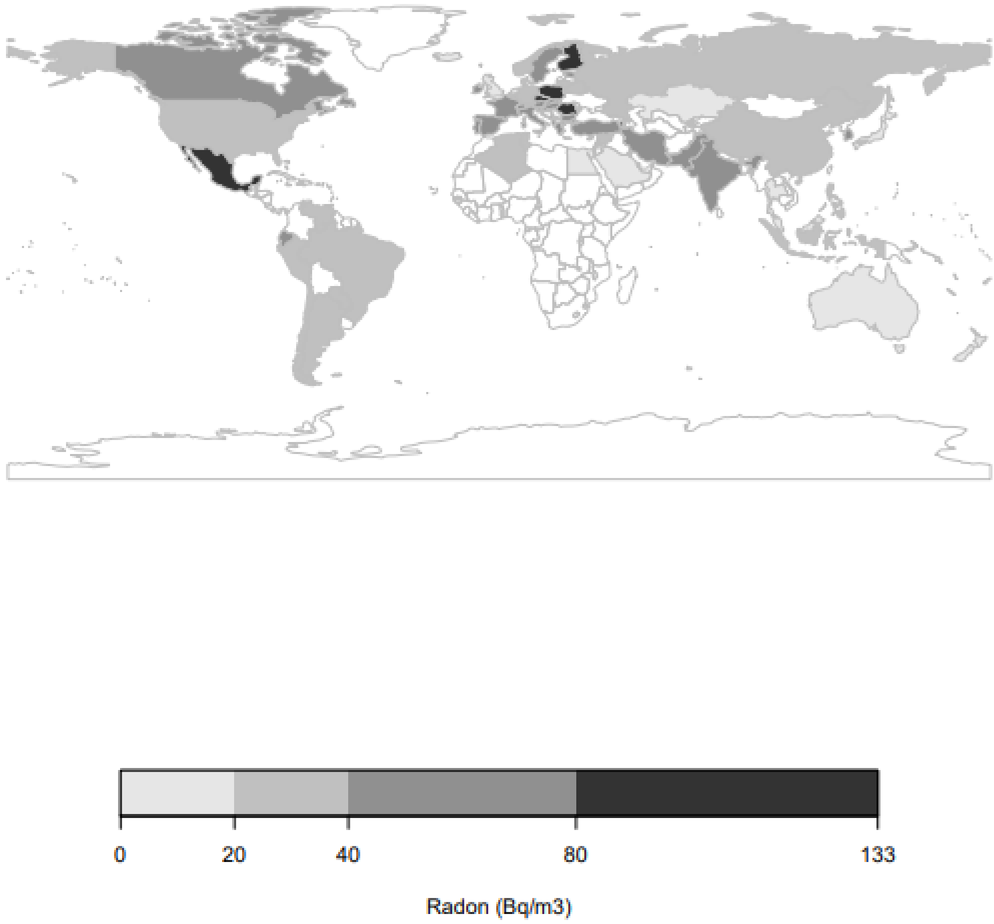

Figure 3: World map of geometric means of national residential radon exposures (Bq/m^3), sources listed in Appendix A Table S1 (plotted using R package rworldmap)

Table 1: Radon population attributable risk (PAR) of lung cancer mortality

Country	Radon[a] GM (GSD) (Bq/m³)	PAR (%) BEIR VI[b] Mean (95% CI)	PAR (%) Hunter[c] Mean (95% CI)	PAR (%) Kreuzer[d] Mean (95% CI)	Attributable number lung cancer deaths BEIR VI[b] Mean (95% CI)	% Total Cancer Deaths[e]
median	38	16.5	14.4	13.6	630	3.0
Albania	75 (2.2)	23.5 (8.1, 36.6)	24.4 (6.8, 37.5)	23.2 (12.5, 32.1)	246 (85, 383)	5.2
Algeria	22 (2.2)	15.8 (3.4, 37.0)	9.0 (2.2, 15.1)	8.3 (4.1, 12.3)	376 (82, 882)	1.7
Argentina	27 (2.2)	13.6 (3.1, 30.7)	10.8 (2.6, 18.0)	10.0 (4.9, 14.7)	1434 (324, 3234)	2.2
Armenia	101 (1.3)	29.3 (22.9, 35.7)	30.1 (9.1, 44.6)	28.9 (16.2, 39)	415 (325, 508)	6.1
Australia	8.7 (2.1)	4.7 (0.9, 13.7)	3.7 (0.8, 6.5)	3.5 (1.6, 5.2)	384 (77, 1128)	0.9
Austria	61 (2.7)	20.9 (1.4, 53.4)	21.0 (5.6, 32.9)	19.8 (10.4, 27.8)	764 (51, 1954)	3.7
Belarus	23 (2.2)	13.4 (2.9, 32.0)	9.5 (2.3, 15.9)	8.8 (4.3, 12.9)	459 (99, 1096)	2.4
Belgium	38 (2.0)	15.2 (4.4, 29.1)	14.3 (3.5, 23.3)	13.5 (6.8, 19.4)	1093 (318, 2088)	3.7
Brazil	30 (2.2)	15.9 (3.7, 33.7)	11.8 (2.9, 19.5)	11 (5.5, 16.1)	4503 (1044, 9541)	2.0
Bulgaria	80 (2.1)	25.8 (9.4, 39.3)	25.8 (7.5, 39.3)	24.4 (13.3, 33.6)	943 (343, 1437)	5.2
Canada	42 (2.8)	16.3 (2.6, 32.4)	15.5 (3.8, 25.1)	14.6 (7.4, 20.9)	3277 (518, 6521)	4.4
Chile	21 (1.8)	9.4 (3.0, 21.0)	8.5 (2.0, 14.4)	7.9 (3.9, 11.7)	279 (89, 627)	1.1
China	34 (2.0)	15.9 (1.5, 38.1)	13.1 (3.2, 21.5)	12.4 (6.2, 18.0)	94931 (8999, 227236)	4.3
Croatia	50 (2.3)	19.3 (4.7, 33.2)	18.0 (4.7, 28.7)	16.9 (8.7, 24.0)	538 (132, 928)	4.0
Cuba	5.2 (3.3)	4.3 (0.3, 20.1)	2.3 (0.5, 4.0)	2.1 (1.0, 3.2)	248 (15, 1158)	1.0
Cyprus	7.0 (2.6)	4.9 (0.5, 18.6)	3.1 (0.7, 5.3)	2.8 (1.3, 4.2)	13 (1, 48)	0.9
Czech Republic	94 (1.8)	24.3 (11.6, 32.9)	28.9 (8.4, 43.3)	27.5 (15.2, 37.2)	1271 (605, 1720)	4.7
Denmark	39 (2.2)	16.0 (3.8, 30.5)	14.6 (3.6, 23.8)	13.7 (6.9, 19.7)	607 (144, 1162)	3.9
Ecuador	70 (2.2)	23.3 (7.9, 35.9)	23.0 (6.2, 35.6)	22.2 (11.9, 30.8)	247 (83, 380)	1.8
Egypt	6.6 (2.2)	5.9 (1.1, 18.0)	2.9 (0.7, 5.0)	2.6 (1.2, 4.0)	266 (47, 808)	0.4
Estonia	44 (2.2)	16.3 (4.1, 29.8)	16.3 (4.1, 26.3)	15.3 (7.8, 21.9)	108 (27, 198)	3.0

Country	Radon[a] GM (GSD) (Bq/m^3)	PAR (%) BEIR VI[b] Mean (95% CI)	PAR (%) Hunter[c] Mean (95% CI)	PAR (%) Kreuzer[d] Mean (95% CI)	Attributable number lung cancer deaths BEIR VI[b] Mean (95% CI)	% Total Cancer Deaths[e]
Finland	84 (2.1)	21.6 (7.8, 34.6)	26.5 (7.3, 40.3)	25.3 (13.8, 34.6)	462 (168, 740)	4.1
France	50 (2.0)	19.4 (6.2, 32.5)	17.8 (4.6, 28.4)	16.9 (8.7, 24.0)	6084 (1957, 10202)	3.9
Germany	37 (2.2)	14.9 (3.6, 29.8)	14.0 (3.4, 22.9)	13.1 (6.6, 18.9)	6449 (1548, 12950)	3.0
Greece	44 (2.4)	15.5 (3.3, 29.2)	16.1 (4.0, 26.1)	15.2 (7.8, 21.8)	996 (213, 1876)	3.5
Hungary	62 (2.1)	23.3 (7.8, 36.0)	21.4 (5.8, 33.4)	20.1 (10.6, 28.2)	1880 (633, 2904)	6.2
Iceland	7.3 (2.2)	4.2 (0.7, 13.1)	3.2 (0.7, 5.5)	2.9 (1.4, 4.4)	6 (1, 19)	1.1
India	42 (2.2)	23.8 (6.6, 41.7)	15.6 (4.2, 25.1)	14.7 (7.5, 21.1)	15175 (4211, 26612)	2.2
Indonesia	35 (1.2)	17.5 (13.1, 22.7)	13.5 (3.4, 22.0)	12.5 (6.3, 18.2)	5418 (4047, 7001)	2.8
Iran	61 (2.2)	24.8 (8.0, 38.0)	20.8 (5.7, 32.6)	19.9 (10.5, 28.0)	1080 (350, 1657)	2.0
Ireland	51 (2.4)	17.6 (3.9, 30.9)	18.1 (4.6, 29.0)	17.1 (8.9, 24.3)	313 (70, 550)	3.7
Israel	23 (2.2)	11.1 (2.3, 27.4)	9.2 (2.1, 15.4)	8.6 (4.2, 12.7)	217 (45, 536)	2.0
Italy	52 (2.1)	15.9 (4.5, 27.3)	18.3 (4.6, 29.3)	17.5 (9.1, 24.8)	5327 (1495, 9147)	3.1
Japan	10.4 (2.0)	4.2 (0.9, 11.7)	4.4 (0.9, 7.6)	4.1 (2.0, 6.2)	3117 (688, 8784)	0.8
Kazakstan	11 (2.2)	7.9 (1.5, 23.1)	4.7 (1.1, 8.2)	4.3 (2.1, 6.5)	334 (63, 973)	1.4
Kuwait	27 (1.9)	18.1 (0.4, 57.1)	10.5 (2.6, 17.5)	9.9 (4.9, 14.5)	15 (0, 48)	1.9
Lithuania	37 (2.5)	16.9 (1.1, 46.1)	13.9 (3.4, 22.7)	12.9 (6.5, 18.7)	219 (15, 596)	2.6
Luxembourg	70 (2.0)	21.9 (8.2, 32.4)	23.2 (6.3, 36.0)	22.1 (11.8, 30.7)	48 (18, 71)	4.7
Malaysia	10 (2.2)	8.3 (1.6, 23.9)	4.4 (1.0, 7.6)	4.1 (1.9, 6.1)	342 (65, 990)	1.6
Mexico	82 (1.3)	26.7 (20.3, 32.9)	25.9 (7.3, 39.5)	24.9 (13.6, 34.2)	2030 (1541, 2503)	2.6
Montenegro	50 (3.2)	24.4 (3.4, 51.8)	18.0 (5.0, 28.5)	16.9 (8.7, 24.0)	84 (12, 178)	6.2
Netherlands	12 (2.0)	7.3 (0.9, 23.2)	5.2 (1.2, 8.9)	4.8 (2.3, 7.2)	773 (97, 2466)	1.8
New Zealand	20 (1.6)	10.2 (1.8, 27.3)	8.0 (1.8, 13.5)	7.4 (3.6, 11.0)	170 (30, 452)	2.0
Norway	38 (3.2)	15.4 (1.7, 34.7)	14.3 (3.5, 23.4)	13.4 (6.8, 19.3)	341 (37, 769)	3.2
Pakistan	52 (2.2)	24.0 (7.0, 39.2)	18.6 (5.1, 29.4)	17.4 (9.0, 24.6)	1443 (420, 2355)	1.4
Paraguay	21 (2.2)	11.5 (2.4, 29.1)	8.4 (2.0, 14.1)	7.8 (3.8, 11.5)	76 (16, 192)	1.5

Country	Radon[a] GM (GSD) (Bq/m^3)	PAR (%) BEIR VI[b] Mean (95% CI)	PAR (%) Hunter[c] Mean (95% CI)	PAR (%) Kreuzer[d] Mean (95% CI)	Attributable number lung cancer deaths BEIR VI[b] Mean (95% CI)	% Total Cancer Deaths[e]
Peru	24 (2.2)	13.1 (2.9, 30.5)	9.4 (2.2, 15.8)	8.9 (4.3, 13.0)	328 (72, 765)	1.3
Philippines	22 (1.1)	12.3 (10.0, 15.0)	9.0 (2.2, 15.0)	8.3 (4.0, 12.2)	1275 (1033, 1553)	2.2
Poland	133 (1.9)	28.4 (15.8, 43.5)	36.1 (11.6, 51.8)	34.8 (20.3, 45.7)	6639 (3691, 10174)	7.0
Portugal	45 (2.2)	18.4 (4.8, 32.9)	16.5 (4.2, 26.5)	15.5 (8.0, 22.2)	633 (166, 1132)	2.6
Rep. of Korea	49 (2.0)	16.8 (5.3, 29.1)	17.5 (4.4, 28.1)	16.6 (8.5, 23.6)	2993 (939, 5197)	3.7
Romania	84 (2.5)	26.3 (7.6, 48.4)	26.7 (7.8, 40.4)	25.4 (13.9, 34.7)	2650 (762, 4879)	5.5
Russian Fed.	35 (2.2)	16.9 (3.9, 33.8)	13.6 (3.4, 22.3)	12.7 (6.4, 18.4)	8583 (1994, 17191)	2.9
Saudi Arabia	16 (2.2)	12.2 (2.5, 31.7)	6.7 (1.6, 11.4)	6.2 (3.0, 9.3)	90 (18, 233)	1.0
Slovakia	48 (3.3)	19.7 (2.4, 45.8)	17.5 (4.5, 28.0)	16.3 (8.4, 23.3)	391 (47, 907)	3.3
Slovenia	60 (2.2)	21.5 (6.2, 34.3)	20.7 (5.5, 32.5)	19.6 (10.3, 27.6)	243 (70, 388)	4.1
Spain	53 (2.5)	18.5 (4.2, 32.4)	18.7 (4.8, 29.8)	17.8 (9.2, 25.1)	3914 (883, 6849)	3.8
Sweden	67 (2.2)	19.2 (6.0, 30.3)	22.4 (5.9, 34.9)	21.2 (11.3, 29.6)	710 (220, 1119)	3.2
Switzerland	51 (2.3)	19.6 (1.4, 49.5)	18.2 (4.7, 29.0)	17.2 (8.9, 24.4)	627 (46, 1580)	3.8
Syria	33 (2.2)	16.3 (4.0, 33.8)	12.6 (3.2, 20.7)	11.7 (5.9, 17.1)	298 (74, 617)	2.1
Thailand	16 (1.2)	9.4 (6.7, 12.6)	6.7 (1.6, 11.3)	6.2 (3.0, 9.2)	1660 (1191, 2228)	2.0
Tunisia	34 (2.2)	17.5 (4.2, 34.8)	13.0 (3.3, 21.2)	12.1 (6.1, 17.6)	271 (66, 541)	3.7
Turkey	57 (2.3)	24.7 (6.9, 40.0)	20.1 (5.6, 31.4)	18.9 (9.9, 26.6)	5422 (1509, 8773)	5.9
UK	14 (3.2)	8.0 (0.6, 26.5)	5.8 (1.3, 10.1)	5.4 (2.6, 8.1)	2858 (219, 9419)	1.8
USA	25 (3.1)	12.5 (1.3, 30.6)	9.9 (2.3, 16.7)	9.3 (4.6, 13.6)	20925 (2137, 51296)	3.4
Venezuela	39 (2.2)	19.4 (4.9, 36.1)	14.5 (3.7, 23.6)	13.7 (6.9, 19.7)	746 (188, 1391)	3.2

The estimates of the national radon PAR of lung cancer mortality for the 66 countries included in the present analysis are listed in Table 1, for the BEIR VI EAC model, the Hunter et al. (2013) model restricted to less than 300 WLM, and the Kreuzer et al. (2015) model for excess rate ratio. The mean PAR using the BEIR VI EAC model ranged from 4.2% (95% CI: 0.9, 11.7) for Japan to 29.3% (95% CI: 22.9, 35.7) for Armenia, with a median for the 66 countries of 16.5%. The three estimates are consistent, with the median for the 66 countries of 16.5%, 14.4% and 13.6% for the BEIR VI EAC model, the Hunter model and the Kreuzer model, respectively. One difference between the three estimates results from the higher excess rate ratio for nonsmokers compared to smokers in the BEIR VI EAC model; a higher mean PAR is estimated for Mexico, at 26.7%, than for Romania, at 26.3%, despite Mexico having a slightly lower GM radon than Romania, at 82 and 84 Bq/m^3, respectively, because the smoking prevalence for males and females are lower in Mexico than in Romania. A lower mean PAR is estimated for Mexico than for Romania using the Hunter model, at 25.9% for Mexico and 26.7% for Romania, and using the Kreuzer model, at 24.9% for Mexico and 25.4% for Romania.

Estimates of the number radon attributable lung cancer deaths using the BEIR VI EAC model for the 66 countries totaled 226,057 in 2012 are also listed in Table 1. The most populous country in the world, China, is the country with the highest estimated number of radon attributable lung cancer deaths, at 94,931 (95% CI: 8,999 - 227,236). The US is ranked 2nd, with 20,925 (95% CI: 2,137 – 51,296) radon attributed lung cancer deaths in 2012, and India is ranked 3rd, with 15,175 (95% CI: 4,211 – 26,612). Radon attributable lung cancer deaths represented a median of 3.0% of total cancer deaths for the 66 countries, ranging from 7.0% for Poland down to 0.4% for Egypt.

2.4.1 Validation

An alternative life table analysis was conducted for Canada using the 2012 age- and sex-specific all-cause and lung cancer mortality rates, using 10,000 simulations of the BEIR VI EAC model for the excess rate ratio from radon. The mean PAR in Canada for lung cancer mortality from radon was estimated to be 14.7% (95% CI: 2.0, 30.0) from the life table analysis, which was similar to the PAR estimate of 16.3% (95% CI: 2.6, 32.4) from the main analysis for Canada derived from the attributable fraction approach using the BEIR VI EAC model. The life table analysis for Canada estimated PAR for males at 13.2% (95% CI: 1.7, 26.7), for male nonsmokers at 19.8% (95% CI: 2.7, 40.0) and for male smokers at 10.9% (95% CI: 1.4, 22.3), and PAR for females at 16.5% (95% CI: 2.2, 33.3), for female nonsmokers at 21.2% (95% CI: 3.0, 41.9) and for female smokers at 13.4% (95% CI: 1.7, 27.7).

Published estimates of national PAR of lung cancer mortality from residential radon exposure for another eight countries are compared to the estimates from this analysis in Table 2. The methodologies used in these studies included the attributable fraction approach, the period life table analysis and one study used the cohort life table analysis, whereas the excess relative risk of lung cancer from radon was modeled using the estimate from pooled case-control residential studies in Europe and North America based on a 30 year exposure period and the BEIR VI EAC model, which is based on lifetime exposure from extrapolation of miner studies.

2.5 Discussion

The estimates of PAR for lung cancer mortality from residential radon for the 66 countries are very similar for the three excess rate ratio models used in this analysis: the median PAR was 16.5% using the BEIR VI EAC model, 14.4% using the Hunter et al. (2013) restricted model and 13.6% using the Kreuzer et al. (2015) model. The estimates support the use of models based on miner studies, with the two miner models based on low radon exposure rates and cumulative doses that approximate those resulting from lifetime residential exposures yielding PARs close to those from the BEIR VI EAC model. The BEIR VI EAC model is the most complete excess rate ratio model, including factors for smoking status, time since exposure, radon exposure rate, and attained age. The three excess rate ratio models used in this analysis to estimate PAR were based on lifetime exposure, calculated from lifetime risk as presented in Equation 2. Four excess rate ratio models, including the three in this analysis, were used in Hunter et al. (2015) to estimate risk of exposure-induced death from residential radon exposure between ages 30 and 75 years. The fourth excess rate ratio model included in Hunter et al. (2015) was the model derived from the European pooled residential study; after corrections for uncertainties in radon measurement, the European pooled residential radon study estimate of ERR=0.16 per 100

Bq/m^3 radon exposure 5-35 years prior to lung cancer (Darby et al. 2006b) was found to be equivalent to an ERR/WLM=0.012, very close to the ERR/WLM=0.013 derived from the Kreuzer et al. (2015) miner model based on low radon exposure rates (Hunter et al. 2015).

The studies of radon attributed lung cancer mortality in miners were characterized by far superior radon exposure assessment, based on annual measurements of radon for each year a miner was exposed, whereas the residential radon studies relied on only one or two measurements for the entire 30 year period of exposure considered. It is reassuring that estimates of PAR derived from extension of the pooled residential studies, after restriction to the better radon exposure measurement, were comparable though lower (see Appendix A Table S3) than those derived from the miner cohort studies. Any degree of residential mobility has a severe impact on the precision of residential radon exposure in the pooled case-control studies. The excess relative risk per 100 Bq/m^3 radon increased from 8% to 16% when the European analysis was adjusted for the random uncertainties from using limited measurements of residential radon (Darby et al. 2006b). Similarly, after consideration of spatial mobility of participants, the ERR per 100 Bq/m^3 radon in the North American pooled residential study increased from 10% to 18% when the analysis was restricted to individuals with measurements for at least 20 of the 25 years of radon exposure (Krewski et al. 2006). As noted by Field and Withers (2012), any remaining non-differential radon exposure measurement error would tend to bias the observed association toward the null and it is quite possible that more precise radon measurement in residential studies (such as based on annual radon levels) would result in a higher estimate for ERR. The policy implications from basing decisions on epidemiologic studies with significant measurement error in environmental exposure and outcomes have been discussed recently by Edwards and Keil (2017).

The Global Burden of Disease Study 2010 (Lozano et al. 2012) reported that the number of lung cancer deaths globally has increased by 47% between 1990 and 2010, to 1527.1 (95% CI: 1126.3, 1779.4) thousand deaths. Tobacco use remains the most important risk factor for lung cancer, but characterizing the contribution of other modifiable risk factors, such as exposure to radon and to outdoor air particulates, is necessary to reduce the burden of lung cancer mortality. The estimates of the global population attributable fraction of lung cancer mortality in 2012 from radon, ranging from 16.5% to 13.6% were comparable to the 12.8% attributable to outdoor air particulates ($PM_{2.5}$) (Evans et al. 2013). This analysis demonstrates that residential radon is a significant and modifiable risk factor for lung cancer mortality worldwide.

The demographics of a country affect the national number of lung cancer deaths. Lung cancer mortality increases with age, so countries with higher life expectancies have a greater number of lung cancer deaths. In 2012, life expectancy was 79 years in the US and 68 years in India (World Bank 2014). Even though the radon exposure is higher and the population is much greater in India than in the US, there are more lung cancer deaths attributed to radon in the US (20,925) than in India (15,175).

The validity of estimating the population radon attributable risk of lung cancer mortality from the attributable fraction approach is supported by the results from the attributable fraction approach and the life table analysis for Canada, with PARs of 16.3% (95% CI: 2.6, 32.4) and 14.7% (95% CI: 2.0, 30.0), respectively. Similar results were reported for the Canadian province of Ontario from a life table analysis (Peterson et al. 2013) using the same BEIR VI EAC model for excess rate ratio: an overall PAR of 13.6%, with PARs of 21.9% for never smokers and 12.3% for ever smokers (radon distribution geometric mean (SD): 43 (3.1) Bq/m^3 for Ontario and 41.9 (2.8) Bq/m^3 for Canada). A life table analysis for Canada also based on a BEIR VI model for excess rate ratio reported a comparable estimate of radon PAR of lung cancer mortality of 16% (Chen et al. 2012).

The estimates determined in this analysis were compared to published national estimates of PARs for eight other countries in Table 2. The estimates in Table 2 determined using the excess rate ratio derived from the pooled residential studies were roughly half those using the BEIR VI models, following the pattern observed for the estimates of PAR determined in this analysis. The PARs determined using the excess rate ratio from pooled residential studies were closer when corrected for uncertainties in the exposure assessment to those using the BEIR VI EAC model for both France (Catelinois et al. 2006), at 11% and 12%, respectively, and for Germany (Menzler et al. 2008), at 7% and 12%, respectively. Use of the ERR estimate from the residential studies assumes that radon exposure greater than 30 years prior does not contribute to lung cancer. The BEIR VI EAC model uses relative weights to progressively diminish the contribution of radon exposure 15-24 years prior and greater than 25 years prior to the outcome, and the Hunter et al. (2013) model diminishes the contribution to one-sixth for exposure greater than 25 years prior to the outcome. However, it is not surprising that PAR estimates of lung cancer mortality from radon based on lifetime exposure are higher than those limited to exposure 30 years prior to lung cancer mortality.

The studies listed in Table 2 also used various measures of radon exposure: the arithmetic mean national exposure for the Netherlands and Sweden (Leenhouts and Brugmans 2001), the radon distribution for the UK (Health Protection Agency 2009) and the US (National Research Council 1999), while regional radon distributions were used for the estimate for France (Catelinois et al. 2006), Germany and Switzerland (Menzler et al. 2008), and South Korea (Lee et al. 2015). The published regional analysis for France reported a smaller PAR estimate (13% versus 19.4%) while the regional analysis for South Korea reported a larger PAR estimate of 22% versus 16.8% when compared to the results from the national analysis used in this study (using the EAC risk model). The estimates from published studies that also used a national analysis were much closer to the results from this study (for the EAC radon model), the US (13.9% versus 12.5%) and the UK (6% versus 8%).

The results of this analysis must be interpreted cautiously due to the uncertainty associated with the national radon exposures. Many countries have not conducted a population representative national survey, and very few countries have conducted more than one representative national radon survey. A population representative national radon survey requires long term radon measurement, 3 to 12 months in duration, in several hundred to several thousand randomly selected dwellings. Some uncertainty is also associated with the excess rate ratio model for lung cancer mortality from radon, as indicated by the range in PAR values resulting from the different excess rate ratio models used in this analysis. The use of the BEIR VI EAC model resulted in the highest estimate of median PAR (16.5%) and the use the excess rate ratios based on the pooled residential studies resulted in the lowest estimates

(10.4% for N. American; 8.4% for European), whereas the excess rate ratio models from recent low dose miner cohort resulted in intermediate estimates of PAR (14.4% for Hunter; 13.6% for Kreuzer).

Table 2: Comparison of national estimates of PAR for lung cancer mortality from radon

	PAR Estimates (%), mean (95% CI)[a]			**Published Estimates**		
Country	**BEIR VI EAC**	**Hunter**	**Kreuzer**	**PAR (ERR model)[b]**	**Methodology**	**Source**
France	19.4 (6.2, 32.5)	17.8 (4.6, 28.4)	16.9 (8.7, 24)	13 (EAC) 5 (Euro. pooled) 2 (N Am pooled) 11 (N Am pooled cor.)	Attributable fraction, regional analysis	Catelinois et al. (2006)
Germany	14.9 (3.6, 29.8)	14.0 (3.4, 22.9)	13.1 (6.6, 18.9)	12 (EAC) 3.1 (Euro. pooled) 7.3 (Euro. pooled cor.)	Period lifetable	Menzler et al. (2008)
Nether-lands	7.3 (0.9, 23.2)	5.2 (1.2, 8.9)	4.8 (2.3, 7.2)	3 (2-mutation carc.)	Cohort lifetable	Leenhouts & Brugman (2001)
Sweden	19.2 (6.0, 30.3)	22.4 (5.9, 34.9)	21.2 (11.3, `29.6)	19 (2-mutation carc.)	Cohort lifetable	Leenhouts & Brugman (2001)
Switzer-land	19.6 (1.4, 49.5)	18.2 (4.7, 29.0)	17.2 (8.9, 24.4)	8.3 (Euro. pooled)	Period lifetable	Menzler et al. (2008)
South Korea	16.8 (5.3, 29.1)	17.5 (4.4, 28.1)	16.6 (8.5, 23.6)	22 (EAC) 8.3 (Euro. pooled)	Attributable fraction, regional analysis	Lee et al. (2015)
US	12.5 (1.3, 30.6)	9.9 (2.3, 16.7)	9.3 (4.6, 13.6)	13.9 (EAC)	Period lifetable	NRC (1999)
UK	8.0 (0.6, 26.5)	5.8 (1.3, 10.1)	5.4 (2.6, 8.1)	6.0 (EAC) 3.3 (Euro. pooled cor.)	Period lifetable	HPA (2009)

Notes: a) Brief information about the three models for excess rate ratio used in this analysis: BEIR IV EAC – BEIR VI exposure-age-concentration model, Hunter – Hunter et al. (2013) model, Kreuzer – Kreuzer et al. (2015) model; b) information about the models used in published studies: EAC – BEIR VI exposure-age-concentration model, Euro. pooled: ERR = 0. 08 per 100 Bq/m^3 radon, N Am pooled: ERR = 0.1 per 100 Bq/m^3 radon, N Am pooled cor. (North American pooled study restricted to lower residential mobility) ERR = 0.18 per 100 Bq/m^3 radon, Euro. pooled cor. (European pooled study corrected for random uncertainties in radon measurement) ERR = 0.16 per 100 Bq/m^3 radon, 2-mutation carc. (the 2-mutation carcinogenesis model is a biologically based carcinogenesis model).

Representative national surveys of residential radon are required in all countries to better characterize the global burden of lung cancer mortality attributed to radon. Reducing the burden of lung cancer mortality and morbidity attributed to radon will depend on future research into the practical implementation and cost-effectiveness of interventions to reduce radon exposures and improved education and awareness about radon. Many countries could benefit from a radon reduction intervention such as the installation of a soil gas membrane at the time of construction, as determined for Norway (Stigum et al. 2003), the UK (Gray et al. 2009) and Ireland (Pollard and Fenton 2014). A highly effective intervention, such as active sub-slab depressurization, might prove cost-effective in countries or regions with higher burdens from radon attributed lung cancer mortality and substantial investment in healthcare.

2.6 Conclusions

Representative national surveys of residential radon exposures were available for 66 countries around the world. The estimates of the population attributable risk of lung cancer mortality from residential radon exposure for 2012 were very consistent for the 66 countries, with a median PAR of 16.5%, 14.4%, and 13.6% from the three excess rate ratio models (BEIR VI EAC, Hunter et al. (2013) restricted and Kreuzer et al. (2015) unrestricted, respectively). An alternative methodological approach, the period life table analysis, was conducted for Canada, and yielded an estimate of PAR of 14.7% (95% CI: 2.0, 30.0) that was very close to the PAR of 16.3% (95% CI: 2.6, 32.4) determined from the attributable fraction approach. This study provides an estimate of the global burden from lung cancer attributable to radon, pending more complete data on national radon exposures.

2.7 References

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Chapter 3 - Utility Gains from Reductions in the Modifiable Burden of Lung Cancer Attributable to Residential Radon in Canada

3.1 Abstract

Research Question: The objective of this analysis is to estimate the modifiable burden of disease according to the annual number of lung cancer deaths prevented and the associated period gain in quality-adjusted life years (QALYs) for the 2012 populations in Canada from reductions in residential radon exposures.

Interventions: Two postulated interventions for residential radon mitigation in new construction are assessed, corresponding to a 50% reduction and an 85% reduction in radon nationally, in the provinces/territories, and in 17 census metropolitan areas in Canada.

Methods: Data were derived from two recent Canadian radon surveys conducted by the Radiation Protection Bureau, Health Canada, along with Canadian mortality and quality of life data. Analyses adopted a lifetime horizon and a discount rate of 1.5%. A period life-table analysis was conducted using age-and sex-specific all cause and lung cancer mortality rates, adjusted for smoking, and the BEIR VI exposure-age-concentration model for radon-attributable risk of lung cancer mortality.

Results: A reduction in residential radon by 50% could prevent 681 lung cancer deaths, associated with a gain of 15,445 QALYs in the Canadian population at a discount rate of 1.5%; a reduction in radon by 85% could prevent 1,263 lung cancer deaths, associated with a gain of 26,336 QALYs. On a per population basis, the Yukon was estimated to benefit most from radon mitigation.

Conclusion: The magnitude of QALY gains in Canada estimated under the two radon mitigation scenarios is appreciable, but varies considerably across provinces due to variability in indoor radon concentrations and smoking rates.

3.2 Background

Radon is a naturally occurring radioactive gas that was identified as a human carcinogen by the International Agency for Research on Cancer (IARC) in 1988 (Dunn and Cooper 2014). Radon is produced when uranium-238 in the ground undergoes radioactive decay, and can collect in houses after entering from the surrounding soil via various entry points (such as cracks in concrete and gaps around service pipes). Following inhalation of radon gas and some short-lived radon progeny, the alpha particles emitted in radioactive decay can damage cellular deoxyribonucleic acid (DNA) in the lung tissue. Radon is an important and modifiable cause of lung cancer, second only to smoking.

In Canada, lung cancer is the second most common cancer (accounting for 14% of all cancers among men and women combined). Lung cancer has the highest mortality rate, with 27% of all cancer deaths attributable to lung cancer for men and women combined (Canadian Cancer Society et al. 2014). Ranked second only to ischemic heart disease among causes of premature death in Canada in 2010, it was estimated that 354 thousand years of life were lost to lung cancer, representing an increase of 21% from 1990 (IHME 2013).

The burden of disease from residential radon in Canada has been assessed in terms of population attributable risk (PAR) for lung cancer mortality. The population attributable risk of lung cancer for residential radon in Canada has recently been estimated to be 16% (Chen et al. 2012), with the population attributable risk in Ontario estimated at 13.6% (Peterson et al. 2013). A range of models for excess relative risk and for the residential radon distribution in Canada were evaluated recently (Al-arydah 2017), with PAR reported as ranging from 11.9% to 19.4% for male ever-smokers, from 12.6% to 20.4% for female ever-smokers, from 19.6% to 41.8% for male never-smokers, and from 19.5% to 44.3% for female never-smokers. The burden in terms of PAR can only be reduced because it is only possible to reduce and not eliminate residential radon. These studies have also estimated the cases of lung cancer that could be prevented in existing housing if residential radon exposures above a specific threshold were mitigated. The modifiable burden of lung cancer attributable to radon was evaluated according to DALY gains from a theoretical reduction of above-threshold radon in existing housing for five provinces in Canada, with the largest potential DALY gains estimated for Quebec and Ontario (Al-arydah 2018).

This study evaluates a strategy to reduce population radon exposures using radon interventions that shift the entire distribution to lower radon concentrations to maximize the number of lung cancer cases prevented. Passive preventive measures installed at construction and active depressurization systems are the two interventions that have been implemented and evaluated for radon control in new construction. A recent review paper of radon control in new homes (Angell 2012) summarized studies of the installation and effectiveness of both passive preventive measures and active soil depressurization systems. It was estimated that 73% of lung cancer deaths attributable to residential radon in Ontario (Peterson et al. 2013) and 85% in the UK (Gray et al. 2009) would result from exposures below 100 Bq/m^3.

Quality-adjusted life years have more recently been identified as the preferred metric for assessment of the health benefits of interventions in Canada by the Canadian Agency for Drugs and Technologies in Health (CADTH). QALYs use a preference-based assessment of the health-related quality of life, with a value between 1 for perfect health and 0 for death, for each life year gained. Health technology assessments in Canada increasingly report cost effectiveness ratios ($/QALY) to make health system decision making more explicit and to improve transparency and public involvement (Jaswal 2013).

This analysis evaluates the burden of disease from radon attributed lung cancer mortality in terms of QALYs that it would be possible to eliminate should current interventions for new housing be implemented across the population, assessed for Canada, each province and territory, and 17 census metropolitan areas. Different populations within Canada are included because radon in indoor air has been determined by the courts to be under areas of health and the environment and so under shared federal, provincial and municipal jurisdiction (Dunn and Cooper 2014). This study also considers the relative risk of overall mortality and lung cancer mortality between current smokers, and former smokers according to time since quitting, compared to nonsmokers. The changes in age-specific smoking status impact the model because current smoking rates peak between the ages of 20 and 35 years and then decrease while lung cancer mortality increases with age. Estimation of the modifiable burden of lung cancer in terms of QALYs per 100,000 population helps to identify populations that would benefit most from investment in radon prevention because both the QALYs gains and the costs of reducing residential radon vary with the population size.

3.3 Research Question

The objective of this analysis is to estimate the modifiable burden of disease according to the annual number of lung cancer deaths prevented and the associated 5 year period gain in QALYs for the 2012 populations in Canada from two interventions to prevent radon entry into new construction applied to the population at the national level, for each province/territory, and for 17 census metropolitan areas (CMAs).

3.4 Methods

3.4.1 Target populations

The national and provincial/territorial populations from 2012 in Canada are modelled with replacement over the 100 year period of the analysis (Statistics Canada 2012b). The populations of the following 17 CMAs were derived from the 2011 Census data (Statistics Canada 2011a): St. John's (NL), Halifax (NS), St. John (NB), Quebec (QC), Sherbrooke (QC), Montreal (QC), Ottawa-Gatineau (NCR), Kingston (ON), Toronto (ON), Windsor (ON), Winnipeg (MB), Saskatoon (SK), Regina (SK), Edmonton (AB), Calgary (AB), Kelowna (BC), and Vancouver (BC).

3.4.2 Intervention strategies

The base scenario in this analysis is described by the current residential radon distribution determined in the representative national radon survey of 2009-2011 (Health Canada 2012). Two interventions to prevent radon entry into new construction are compared to the base scenario in this analysis: having passive preventive radon measures such as radon protective membrane and sealing joints and cracks in the floor and foundations, and secondly, depressurization with an active fan-powered system. The passive preventive measures typically yield about a 50% reduction in radon levels (Woolliscroft et al. 1994), determined from a comparison of radon levels in new construction with and without radon membranes installed for selected sites with high radon levels in Devon and Cornwall in the UK. An active (fan-powered) depressurization system was conservatively assumed to result in about an 85% reduction in radon levels, as reported from field trials in Denmark (Andersen et al. 1997). A recent summary of radon reduction in 52 houses after installation of active depressurization systems in Canada reported an average radon reduction of 91% (Health Canada 2016). This analysis considers the theoretical scenarios of population-wide radon reduction in the proportion of housing where occupants are exposed to radon (excluding upper floor apartments/condos), listed in Table 3, to estimate the maximum potential benefit of these interventions (the modifiable radon burden).

3.4.3 Study perspective and time horizon

A societal perspective and a lifetime horizon were adopted for this study because residential radon exposure is lifelong and lung cancer mortality in Canada peaks between age 75 and 89 years.

3.4.4 Discounting

The discount rate used for the base analysis is 1.5%, recommended by the CADTH (CADTH 2017). A discount rate of 0% is also used for comparison purposes.

3.4.5 Modelling

This abridged period life-table approach uses 5 year age intervals, and age-and sex-specific all cause and lung cancer mortality rates calculated from the census and death database. The probabilities of death reported in the death database were first converted into mortality rates, so that an exposed person's risk can be modelled as the sum of the baseline risk and the risk due to radon exposure, expressed in terms of an intensity ratio. The probability of surviving to the beginning of each age interval, of dying during the age interval, and the intensity ratio between all cause and lung cancer mortality are used to determine baseline and exposed life expectancy (LE, LE_E) and lifetime risk (LR, LR_E) of lung cancer. The population attributable risk is calculated using Equation 1 from the population-averaged lifetime risk in the exposed (LR_E) and the baseline lifetime risk for a theoretical unexposed population (LR) as described in Brand et al. (2005):

$$PAR = \frac{LR_E - LR}{LR_E} \qquad (Eq\ 1)$$

3.4.6 Residential radon distribution

The indoor radon distributions for Canada, the provinces/territories, and CMAs are listed in Table 3, defined by the geometric mean and geometric standard deviation. The fitdistrplus function in R using population weights and the maximum likelihood estimator was used to determine the radon distributions from two recent Canadian radon surveys conducted by the Radiation Protection Bureau, Health Canada. The national and provincial/territorial radon distributions were determined from a representative national radon survey conducted between 2009-2011, based on 3 month-long measurements taken during the winter months using passive alpha-track radon detectors from Track Analysis Systems Limited (Health Canada 2012). The radon distributions for the CMAs were determined from a second radon-thoron survey of 33 CMAs in Canada conducted in 2012-2013 (Chen et al. 2015). Residential radon data below the detection limit of 15 Bq/m^3 were approximated in this analysis by half that value, 7.5 Bq/m^3.

Table 3: Radon distribution and radon-exposed housing occupancy, provinces/territories, and census metropolitan areas

Canada, Provinces, Territories	Radon Distribution		Housing Occupancy % (radon exposed)	*CMA*	Radon Distribution		Housing Occupancy % (radon exposed)
	Geo Mean	GSD			Geo Mean	GSD	
Canada	41.7	2.64	86.7				
NL	32.8	2.94	96.9	*St. John's, NL*	62.5	2.34	95.3
NS	38.6	3.34	88.2	*Halifax, NS*	91.3	3.14	78.7
PEI	22.3	2.71	93.2				
NB	62.4	3.55	92.2	*St. John, NB*	70.8	2.74	87.0
QC	36.6	3.04	78.8	*Quebec, QC*	67.4	2.74	75.5
				Sherbrooke, QC	119.8	2.64	77.6
				Montreal, QC	69.4	2.54	71.0
ON	34.4	2.64	78.7	*Ottawa-Gat, CR*	79.1	2.13	78.7
				Kingston, ON	123.2	2.03	80.7
				Toronto, ON	45.3	1.82	67.3
				Windsor, ON	122.5	1.72	86.3
MB	100.1	2.38	85.3	*Winnipeg, MB*	198.9	1.93	79.7
SK	88.0	2.23	90.9	*Saskatoon, SK*	138.5	1.38	85.0
				Regina, SK	240.8	1.93	87.0
AB	64.6	1.99	88.8	*Edmonton, AB*	96.2	1.72	86.7
				Calgary, AB	106.8	1.72	85.0
BC	25.5	2.06	78.2	*Kelowna, BC*	96.7	1.93	88.5
				Vancouver, BC	20.9	1.93	72.7
NU	8.60	1.19	93.4				
NT	39.4	2.93	89.9				
YT	85.7	2.88	94.2				

3.4.7 All Cause and Lung Cancer Mortality by Smoking Status

Current smoking data by sex- and age-specific category in Canada for 2012 (Table 4) used in this analysis was reported nationally and for each province and territory by the Canadian Community Health Survey (CCHS) (Statistics Canada 2013). All cause mortality rates for 2012 were reported in the Death Database (Statistics Canada 2012a) by sex- and age-specific category in Canada, nationally and for each province and territory. Lung cancer mortality rates were assumed to constitute the same proportion of lung cancer incidence rates (Statistics Canada 2012c) as were reported in the National Cancer Institute SEER cancer statistics review for the US population between 1975 and 2009 (Howlader et al. 2012), based on similar patterns of high mortality rates and low life expectancy post diagnosis in both countries. All-cause mortality (including lung cancer) and lung cancer mortality were both adjusted for smoking using the respective relative risk for smokers versus nonsmokers by sex- and age-specific category (Villeneuve and Mao 1994). The values of relative risk of all cause and lung cancer mortality for smokers versus nonsmokers (RR_e) by sex and age category used were those reported by the American Cancer Society Cancer Prevention Study II (ACS CPS-II) (Thun et al. 1997). The CPS II relative risk by age and sex category are given for current (daily and occasional) versus lifelong nonsmokers (Table 4). The population consists of former smokers in addition to current smokers and lifelong nonsmokers. Based on more recent research estimating the relative risk of former smokers according to time since quitting, this analysis modelled smokers who quit more than 20 years prior as lifelong nonsmokers, and assumed a linear decrease in relative risk over a 20 year period for former smokers (Kenfield et al. 2008; Pesch et al. 2012). Due to the small population sizes in the territories (the Yukon, the Northwest Territories and Nunavut), the all-cause and lung cancer mortality rates were averaged over the ten previous years, from 2003-2012.

Table 4: Age-specific HUI, and age- and sex-specific relative risk for all-cause and lung cancer mortality

Age-Group (years)	**HUI Mean (sd)**	**RR all-cause mortality M**	**RR all-cause mortality F**	**RR lung cancer mortality M**	**RR lung cancer mortality F**	**Canada: current smoker, daily or occasional M Mean (95% CI)**	**Canada: current smoker, daily or occasional F Mean (95% CI)**
0-4	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
5-9	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
10-14	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
15-19	0.896 (0.154)	1.0	1.0	1.0	1.0	9.5 (7.8, 11.1)	8.9 (7.3, 10.5)
20-24	0.905 (0.158)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
25-29	0.909 (0.159)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
30-34	0.909 (0.160)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
35-39	0.907 (0.164)	3.0	1.1	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
40-44	0.883 (0.195)	3.2	1.0	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
45-49	0.862 (0.209)	2.8	2.1	7.0	22.1	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
50-54	0.846 (0.221)	3.1	1.9	21.1	11.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
55-59	0.841 (0.219)	3.0	2.2	39.0	16.6	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
60-64	0.846 (0.213)	2.7	2.3	31.3	14.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
65-69	0.846 (0.210)	2.6	2.3	27.0	17.1	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
70-74	0.825 (0.221)	2.5	2.1	26.0	10.2	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
75-79	0.796 (0.243)	2.1	1.9	21.5	12.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
80-84	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
85-89	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
90-94	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
95-99	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)

3.4.8 Excess Relative Risk Model for lung cancer mortality from radon exposure

The sixth committee on Biological Effects of Ionizing Radiation Exposure-Age-Concentration (BEIR VI EAC model based on 11 miner cohorts (NRC 1999) is the most comprehensive radon risk projection model for estimating the age-specific excess rate ratio (excess relative risk per Working Level Month (ERR/WLM)) in relation to cumulative radon exposure, including modifying factors for smoking status, effective exposure duration, exposure-rate effect, and attained age. A working level month is a cumulative exposure defined as breathing a concentration of 1 WL (2.08×10^{-5} J/m^3) for a working month of 170 hours (1 WLM = 6.37×10^5 Bq/m3 per hour for equilibrium equivalent concentration of radon, and assuming an equilibrium factor of 0.4 and 7000 hours per year indoors at home, 1 Bq/m3 radon exposure for 1 year = 0.0044 WLM at home). The smoking adjustment factor for nonsmokers is roughly double that for smokers, the attained age factor decreases with age, and the exposure-rate factor decreases with exposure rate. The effective exposure duration (η_t) is calculated using three weighted periods that exclude the 5 years prior to death (Eq 2) and can therefore incorporate a change in radon exposure rate during the time since exposure modelled:

$$\eta_t = \Delta_{[5,14]}(t) + \theta_2 \Delta_{[15,24]}(t) + \theta_3 \Delta_{[25+]}(t) \qquad (2)$$

And $\Delta_{[a,b]}(t)$ = {10 for $t > b$; (t-a) for $a \le t \le b$; 0 otherwise}

Central estimates of the parameter values for the modifying factors (derived from an overall fit of the BEIR VI EAC model to 11 miner cohort studies taken from Krewski et al. (1999) were described in greater detail in Brand et al. (2005).

3.4.9 Quality of Life

Health related quality of life is characterized using the age-specific values (Table 4) for Health Utilities Index Mark 3 (HUI3), a standardized instrument used as a measure of eight dimensions of health-related quality of life, reported in the CCHS for 2009-10 (Statistics Canada 2010). The change in quality of life is assessed only in terms of mortality (the disutility due to lung cancer morbidity is not included) and will likely lead to results that are conservative.

3.4.10 Analysis

The base analysis models the lung cancer risk associated with current radon exposures. Two interventions to prevent radon entry into new construction were applied to the housing stock exposed to residential radon, and the number of lung cancer deaths prevented and the associated QALYs gained are calculated by comparing each scenario to the base model. The two interventions investigated are preventive radon measures installed at construction, resulting in a 50% reduction in radon, and an active depressurization system, resulting in an 85% reduction in radon. The percentage of housing that is exposed to residential radon for each target population listed in Table 3 was estimated from the 2011 National Household Survey (Statistics Canada 2011b).

3.4.11 Uncertainty

A Monte Carlo simulation with 10,000 samples from the distributions for radon exposure, age-specific health utilities, and lung cancer mortality rates and smoking prevalence by age-group and sex, was conducted to assess the uncertainty. The mean and 95% credible interval (2.5% and 97.5% quantiles of the simulated results) were estimated for the number of lung cancer deaths prevented and associated gain in QALYs for the 2012 Canadian population, each provincial population, and those of 17 CMAs.

3.5 Results

The annual radon attributed lung cancer deaths prevented and associated period QALYs gained and QALYs per 100,000 people gained in Canada for proposed intervention 1 and intervention 2 are listed in Table 5. The results are non-linear with respect to radon reduction for both attributed lung cancer deaths prevented and QALYs gained, with the benefit from an 85% reduction nearly double that from a 50% reduction. The total QALY gain using a discount rate of 1.5% for the Canadian population for intervention 1, a 50% reduction in residential radon, is 15,445 (95% CI: 1,180 - 51,691), and for intervention 2, an 85% reduction in radon, is 26,336 (95% CI: 2,006 - 88,339). For a discount rate of zero, the QALY gains are higher, at 39,253 (95% CI: 2,999 - 131,346) for intervention 1 and 66,953 (95% CI: 5,098 - 224,619) for intervention 2.

The QALY gain for women in Canada is higher than for men across all categories; for example, the QALY gain at a discount rate of 1.5% for intervention 2 was 14,863 (95% CI: 1,134 – 49,853) for women and 11,473 (95% CI: 872 - 38,457) for men. The QALY gain for intervention 2 at a discount rate of 1.5% is 85 per 100,000 women (95% CI: 6 – 285) and 67 per 100,000 men (95%CI: 5 – 223). The QALY gain per 100,000 smokers is higher than per 100,000 nonsmokers for both men and women because radon-attributable lung cancer mortality is more common among smokers. Similarly, the total QALY gain for smokers in the Canadian population is also higher than for nonsmokers, for both men and women, despite the far greater number of nonsmokers than smokers in the population. The QALY gain for intervention 2 at a discount rate of 1.5% for male nonsmokers in the Canadian population is 3,521 (95% CI: 262 - 111,914) and 7,952 (95% CI: 606 - 26,442) for male smokers, and for female nonsmokers is 8,382 (95% CI: 647 - 27,881) and 6,480 (95% CI: 490 - 21,877) for female smokers.

The annual number of preventable radon attributable lung cancer deaths for Canada (Table 5) is 681 (95% CI: 100 – 1,284) for intervention 1 and 1,263 (95% CI: 171 - 2,571) for intervention 2. The number of preventable radon-attributable lung cancer deaths are higher for men than for women, and higher for smokers than nonsmokers for both men and women, because most radon-attributable lung cancer deaths occur in smokers and smoking prevalence is higher among men than women.

Table 5: Canada – period QALYs, QALYs per 100,000 people, and annual radon-attributable lung cancer deaths prevented

Canada	Total	Male	Female	Male nonsmoker	Male smoker	Female nonsmoker	Female smoker
QALYs (DR=0)							
Intervention 1 **Mean** (95% CI)	**39,253** (2,999 – 131,346)	**17,012** (1,297 – 56,891)	**22,241** (1,702 – 74,438)	**5,264** (391 - 17,803)	**11,748** (900 - 38,947)	**9,754** (738 - 32,906)	**12,487** (968 - 41,384)
Intervention 2 **Mean** (95% CI)	**66,953** (5,098 – 224,619)	**29,021** (2,206 – 97,323)	**37,932** (2,893 – 127,267)	**8,953** (665 - 30,289)	**20,069** (1,530 - 66,779)	**16,595** (1,254 - 56,022)	**21,336** (1,646 - 70,981)
QALYs (DR=1.5%)							
Intervention 1 **Mean** (95% CI)	**15,445** (1,180 – 51,691)	**6,728** (513 – 22,495)	**8,717** (667 – 29,179)	**2,071** (154 - 7,003)	**4,657** (357 - 15,437)	**3,809** (288 - 12,852)	**4,908** (381 - 16,268)
Intervention 2 **Mean** (95% CI)	**26,336** (2,006 – 88,339)	**11,473** (872 – 38,457)	**14,863** (1,134 – 49,853)	**3,521** (262 - 11,914)	**7,952** (606 - 26,444)	**6,480** (490 - 21,877)	**8,382** (647 - 27,881)
QALYs per 100,000 people (DR=0)							
Intervention 1 **Mean** (95% CI)	**113** (9 – 378)	**99** (8 – 330)	**127** (10 – 425)	**41** (3 – 137)	**276** (21 – 914)	**68** (5 – 231)	**386** (30 – 1,280)
Intervention 2 **Mean** (95% CI)	**193** (15 – 646)	**168** (13 – 565)	**217** (17 – 726)	**69** (5 – 234)	**472** (36 – 1,568)	**117** (9 – 393)	**659** (51 – 2,196)
QALYs per 100,000 people (DR=1.5%)							
Intervention 1 **Mean** (95% CI)	**45** (3 – 149)	**39** (3 – 131)	**50** (4 – 167)	**16** (1 – 54)	**109** (8 – 363)	**27** (2 – 90)	**152** (12 – 503)
Intervention 2 ***Mean*** *(95% CI)*	**76** (6 – 254)	**67** (5 – 223)	**85** (6 – 285)	**27** (2 – 92)	**187** (14 – 621)	**45** (3 – 153)	**259** (20 – 862)
Radon attributable lung cancer deaths prevented							
Intervention 1 **Mean** (95% CI)	**681** (100 – 1,284)	**357** (50 – 691)	**324** (49 – 593)	**56** (10 – 91)	**301** (40 – 601)	**102** (19 – 162)	**222** (31 – 433)
Intervention 2 **Mean** (95% CI)	**1,263** (171 – 2,571)	**660** (86 – 1,378)	**603** (85 – 1,195)	**107** (18 – 185)	**553** (69 – 1, 911)	**194** (33 - 331)	**409** (52 – 864)

The annual radon attributed lung cancer deaths prevented and associated period QALYs gained and QALYs per 100,000 people gained in the Canadian provinces and territories for proposed intervention 1 and intervention 2 are listed in Table 6. The total QALY gains are highest for provinces with the largest populations, ranging for intervention 2 at a discount rate of 1.5% from 7,045 (95% CI: 450 - 24,771) for Quebec and 6,529 (95% CI: 519 - 24,168) for Ontario to 55 (95% CI: 3 - 202) for the Northwest Territories and 10 (95% CI: 2-30) for Nunavut. The QALY gains per 100,000 population are highest for the areas of highest radon in Canada: at 148 (95% CI: 7 - 536) for New Brunswick, 121 (95% CI: 14 - 302) for Manitoba, 115 (95% CI: 15 - 276) for Saskatchewan and substantially greater in the Yukon, at 702 (95% CI: 52 – 2,152) for intervention 2 at a discount rate of 1.5%. The lowest values are 28 per 100,000 people (95% CI: 6 - 85) for Nunavut and 38 per 100,000 people (95% CI: 4 - 152) for BC. The absolute number of preventable radon attributed lung cancer deaths were also highest for provinces with higher populations, ranging for intervention 2 from 341 (95% CI: 40 – 720) for Quebec to 360 (95% CI: 50 – 797) for Ontario to 1 (95% CI: 0 - 2) for Nunavut and 1 (95% CI: 0 – 3) for the Northwest Territories.

The individual period QALY gains in Canada for the reduction in radon from the geometric mean achieved by intervention 2, by age category for male smokers, male nonsmokers, female smokers and female nonsmokers at discount rate of 0, are plotted in Figure 4. The QALY gains all follow the same trend: zero until about age 50, peaking at age-group 75-79 years, and falling nearly to zero at about age 95. The QALY gains begin to increase after about age 50 because they are associated with the prevention of radon-attributed lung cancer death, and lung cancer mortality rates are very low before age 50. The individual annual QALY gains are higher for smokers than nonsmokers, and higher for females than males.

Table 6: Provinces and CMAs - period QALYs, QALYs per 100,000 people, and annual radon-attributable lung cancer deaths prevented

Province	**QALYs (DR=0)**		**QALYs (DR=1.5%)**		**QALYs per 100,000 people (DR=0)**		**QALYs per 100,000 people (DR=1.5%)**		**Lung cancer deaths prevented**	
CMA	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**
NL	735 (47-2,727)	1,253 (79-4,663)	291 (18-1,079)	495 (31-1,844)	140 (9-518)	238 (15-886)	55 (3-205)	94 (6-350)	15 (2-31)	27 (3-62)
St. John's	308 (33-857)	525 (55-1,462)	122 (13-339)	208 (22-578)	156 (17-435)	266 (28-742)	62 (7-172)	105 (11-294)	5 (1-8)	10 (2-17)
NS	1,461 (72-5,081)	2,492 (122-8,684)	577 (28-2,004)	983 (48-3,424)	155 (8-538)	264 (13-919)	61 (3-212)	104 (5-362)	26 (3-51)	48 (5-103)
Halifax	791 (54-2,494)	1,352 (92-4,276)	313 (21-987)	535 (36-1,691)	203 (14-639)	346 (23-1095)	80 (5-253)	137 (9-433)	11 (2-16)	22 (3-33)
PEI	147 (10-660)	251 (16-1,126)	58 (4-259)	99 (6-442)	102 (7-455)	173 (11-776)	40 (3-178)	68 (4-305)	3 (0-7)	5 (1-13)
NB	1,667 (84-5,995)	2,849 (143-10,304)	658 (33-2,364)	1,124 (56-4,059)	220 (11-792)	377 (19-1,362)	87 (4-312)	148 (7-536)	26 (3-43)	49 (5-87)
St. John	231 (19-647)	394 (33-1,108)	91 (8-256)	155 (13-438)	180 (15-507)	308 (26-867)	71 (6-200)	122 (10-343)	4 (1-6)	7 (1-12)
QC	10,462 (671-36,690)	17,857 (1,141-62,779)	4,129 (265-14,485)	7,045 (450-24,771)	129 (8-454)	221 (14-777)	51 (3-179)	87 (6-306)	183 (23-356)	341 (40-720)
Quebec	1,481 (126-4,050)	2,530 (214-6,938)	584 (50-1,599)	998 (85-2,737)	193 (16-529)	330 (28-906)	76 (6-209)	130 (11-357)	22 (4-33)	42 (7-68)
Sherbrooke	583 (66-1,814)	997 (113-3,123)	230 (26-715)	393 (45-1,229)	289 (33-898)	494 (56-1,547)	114 (13-354)	195 (22-609)	7 (2-9)	14 (4-19)
Montreal	6,109 (551-15,745)	10,433 (937-26,959)	2,410 (218-6,213)	4,115 (370-10,631)	160 (14-412)	273 (25-705)	63 (6-162)	108 (10-278)	93 (19-139)	177 (32-284)
ON	9,715 (774-35,905)	16,560 (1,316-61,322)	3,831 (305-14,157)	6,529 (519-24,168)	72 (6-268)	123 10-457)	29 (2-106)	49 (4-180)	195 (29-399)	360 (50-797)
Ottawa-Gat (NCR)	1,427 (179-3,351)	2,433 (305-5,727)	564 (71-1,325)	962 (121-2,263)	115 (14-271)	197 (25-463)	46 (6-107)	78 (10-183)	24 (6-35)	46 (11-70)

Province	QALYs (DR=0)		QALYs (DR=1.5%)		QALYs per 100,000 people (DR=0)		QALYs per 100,000 people (DR=1.5%)		Lung cancer deaths prevented	
CMA	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**
Kingston	315 (48-694)	537 (81-1,188)	124 (19-273)	212 (32-467)	197 (30-435)	337 (51-745)	78 (12-171)	133 (20-293)	4 (2-5)	8 (3-11)
Toronto	3,327 (440-10,264)	5,669 (748-17,519)	1,314 (174-4,052)	2,238 (295-6,914)	60 (8-184)	102 (13-314)	24 (3-73)	40 (5-124)	71 (16-125)	131 (28-248)
Windsor	625 (118-1,144)	1,067 (200-1,956)	246 (46-451)	420 (79-770)	196 (37-358)	334 (63-613)	77 (15-141)	132 (25-241)	9 (4-11)	17 (6-22)
MB	2,243 (260-5,607)	3,827 (442-9,587)	884 (103-2,210)	1,508 (174-3,777)	179 (21-449)	306 (35-767)	71 (8-177)	121 (14-302)	33 (9-45)	63 (15-91)
Winnipeg	2,987 (583-7,773)	5,101 (992-13,333)	1,177 (230-3,065)	2,010 (391-5,253)	239 (47-622)	408 (79-1,067)	94 (18-245)	161 (31-420)	36 (17-43)	71 (30-87)
SK	1,852 (236-4,440)	3,159 (402-7,588)	730 (93-1,752)	1,245 (159-2,993)	171 (22-409)	291 (37-699)	67 (9-161)	115 (15-276)	29 (8-41)	55 (14-83)
Saskatoon	493 (110-862)	841 (187-1,474)	195 (43-340)	332 (74-582)	189 (42-331)	323 (72-565)	75 (17-131)	128 (28-223)	7 (3-8)	13 (6-17)
Regina	593 (76-1,798)	1,015 (130-3,095)	234 (30-710)	401 (51-1,221)	282 (36-854)	482 (62-1,470)	111 (14-337)	190 (24-580)	6 (2-7)	12 (4-15)
AB	3,201 (418-8,410)	5,454 (711-14,359)	1,269 (166-3,331)	2,161 (282-5,682)	83 (11-217)	141 (18-370)	33 (4-86)	56 (7-146)	68 (17-106)	128 (29-211)
Edmonton	1,312 (230-2,706)	2,236 (392-4,619)	519 (91-1,071)	885 (155-1,827)	113 (20-233)	193 (34-398)	45 (8-92)	76 (13-158)	24 (9-32)	46 (15-65)
Calgary	1,313 (237-2,567)	2,238 (402-4,382)	521 (94-1,019)	888 (160-1,738)	108 (19-211)	184 (33-361)	43 (8-84)	73 (13-143)	24 (9-30)	45 (16-61)
BC	2,574 (286-10,307)	4,383 (487-17,584)	1,014 (113-4,060)	1,726 (192-6,926)	57 (6-227)	96 (11-387)	22 (2-89)	38 (4-152)	58 (10-132)	105 (17-258)
Kelowna	396 (57-848)	676 (97-1,451)	155 (22-333)	265 (38-569)	220 (32-472)	376 (54-807)	86 (12-185)	148 (21-317)	5 (2-7)	10 (3-15)
Vancouver	895 (101-3,744)	1,523 (171-6,384)	353 (40-1,477)	601 (67-2,517)	39 (4-162)	66 (7-276)	15 (2-64)	26 (3-109)	22 (4-54)	39 (6-105)
NU	14 (3-43)	24 (5-73)	6 (1-17)	10 (2-30)	41 (8-123)	70 (14-210)	17 (3-50)	28 (6-85)	0 (0-1)	1 (0-2)

Province	QALYs (DR=0)		QALYs (DR=1.5%)		QALYs per 100,000 people (DR=0)		QALYs per 100,000 people (DR=1.5%)		Lung cancer deaths prevented	
CMA	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**	**Interv. 1**	**Interv. 2**
NT	78 (5-294)	133 (8-501)	31 (2-118)	54 (3-202)	179 (10-674)	305 (18-1,150)	72 (4-271)	123 (7-463)	1 (0-2)	1 (0-3)
YT	372 (28-1,132)	637 (48-1,954)	148 (11-450)	253 (19-776)	1,031 (78-3,140)	1,768 (132-5,420)	410 (31-1,248)	702 (52-2,152)	2 (1-4)	5 (1-8)

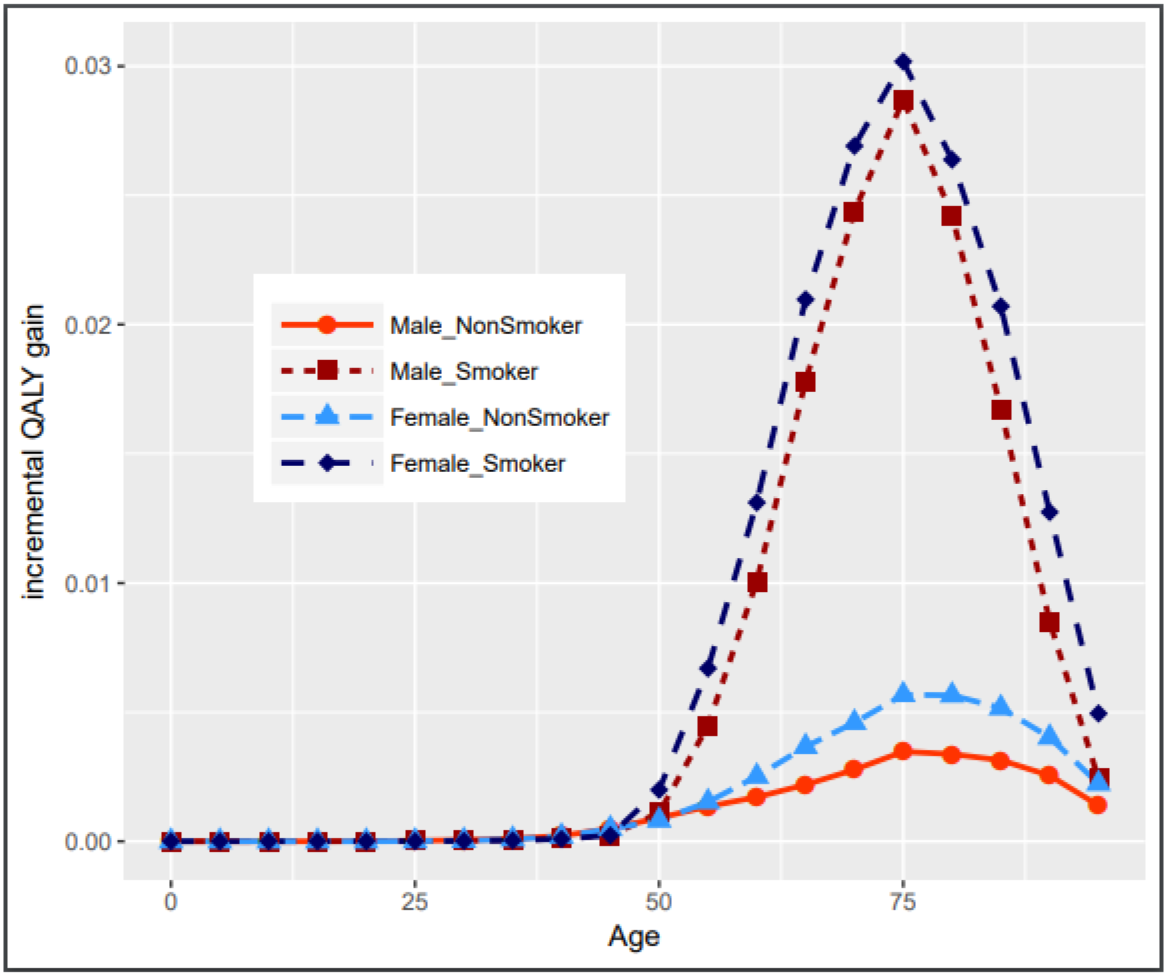

Figure 4: individual period QALY gains in Canada for the reduction in radon from the geometric mean achieved by intervention 2 by age, sex, and smoking status, at discount rate of 0

The annual radon attributed lung cancer deaths prevented and associated period QALYs gained and QALYs per 100,000 people gained in 17 census metropolitan areas in Canada for proposed intervention 1 and intervention 2 are listed in Table 6. The total QALY gains and number of preventable radon-attributable lung cancer deaths are highest for the CMAs with the highest populations. The total QALY gains for intervention 2 at a discount rate of 1.5% range from 4,115 (95% CI: 370 – 10,631) for Montreal, QC, and 2,238 (95% CI: 295 – 6,914) for Toronto, ON to a low of 155 (95% CI: 13 – 438) for St. John, NB. The number of preventable radon-attributable lung cancer deaths for intervention 2 ranges from 177 (95% CI: 32 – 284) for Montreal, QC, and 131 (95% CI: 28 – 248) for Toronto, ON, to 7 (95% CI: 1 – 12) for St. John, NB. The QALY gains per 100,000 people are highest for CMAs with the highest radon exposures: at 195 (95% CI: 22-609) for Sherbrooke, 190 (95% CI: 24-580) for Regina, 161 (95% CI: 31-420) for Winnipeg, and 148 (95% CI: 21-317) for Kelowna (low smoking prevalence and high percentage of housing exposed to radon) for intervention 2 at a discount rate of 1.5%. The lowest QALY gains per 100,000 people for intervention 2 at a discount rate of 1.5% are 26 (95% CI: 3-109) for Vancouver and 40 (95% CI: 5-124) for Toronto, cities characterized by low residential radon and a lower percentage of housing exposed to radon.

3.6 Discussion

Residential radon is an important and modifiable cause of lung cancer in Canada. Smoking is the most important modifiable cause of lung cancer, and although one-third of smokers in Canada express an intention to quit smoking within a month, long-term success is elusive even when it is defined as quitting for 6 or 12 months (CADTH 2011). Radon mitigation is the most important intervention to reduce lung cancer among nonsmokers, and reducing indoor radon benefits all current and future residents of the structure mitigated, regardless of smoking status, over the lifetime of the structure (Conrath and Pawel 2013). The estimates for 5 year period QALY gain from reducing the residential radon levels in Canada by 50% is 15,445 (95% CI: 1,180 - 51,691) and by 85% is 26,336 (95% CI: 2,006 - 88,339), discounted at 1.5% [undiscounted: 39,253 (95% CI: 2,999 - 131,346) and 66,953 (95% CI: 5,098 - 224,619)], and the annual number of preventable radon attributed lung cancer deaths is 681 (95% CI: 100 – 1,284) and 1,263 (95% CI: 171 - 2,571), respectively. The highest QALYs and number of preventable radon-attributed lung cancer deaths among the provinces/territories and CMAs are for those with the highest radon exposures and largest populations. This analysis demonstrates the potential benefits to Canadians from improved life expectancy and quality of life from reducing the radon attributable burden of lung cancer mortality in new housing.

The number of radon attributable lung cancer deaths that might be prevented by theoretical reductions in residential radon were estimated for Canada (Al-arydah 2018; Chen et al. 2012).

Remediation of houses with radon above 800 (200, 100) Bq/m^3 would result in 90 (927, 1704) deaths averted out of a total of 3261 lung cancer deaths attributed to residential radon in Canada (Chen et al. 2012). The concave shape of plots of increasing PAR with increasing action/threshold for radon remediation in existing housing, in all five Canadian provinces assessed, similarly demonstrates that greater relative benefit would be derived for lower action/threshold levels for radon mitigation (Al-arydah 2018). The passive preventive measures and active depressurization systems evaluated in this analysis for new construction reduce the smaller risks experienced by the middle of the distribution and prevent a far greater number of cases of a disease than adopting a strategy preventing only the highest risk, described by Rose (2008) as a "targeted rescue operation for vulnerable individuals" at the tail of the distribution.

The period QALY gains per 100,000 people identify the provinces/territories and CMAs where radon reduction would have the greatest benefit, independent of population size: the Yukon, New Brunswick, Manitoba and Saskatchewan; and Sherbrooke, Regina, Winnipeg, Kelowna and Halifax. The much higher values of QALY gains per 100,000 people for both interventions in the Yukon is the result of the much higher cancer mortality rates recently reported for the Yukon compared to national, provincial, urban and southern-rural jurisdictions (Simkin et al. 2017). Comparison of the Yukon and Canadian 5-year cumulative rolling lung cancer age-standardized mortality rates (ASMRs) by sex demonstrate much higher rates for the Yukon than the Canadian average for both men and women, and that while this difference has decreased for men it has increased for women over the years 1999-2013. The Yukon is a high radon area in Canada, and a greater benefit would be derived from preventing some of this much larger lung cancer burden. Factors that contribute to this burden include higher smoking rates, and physical and cultural barriers to health promotion and care services and end-of-life care.

A global analysis recently quantified the increased mortality and lung cancer from environmental exposure to particulate air pollution (Evans et al. 2013) and the gain in quality-adjusted life expectancy associated with a uniform reduction in sulfate air pollution in Canada was estimated to be 20,960 QALYs discounted at 5% and 25,520 QALYs undiscounted (Coyle et al. 2003). For Canada, the undiscounted period QALY gain for a 50% (85%) reduction in residential radon was about 1.5 (2.5) times the undiscounted annual QALY gain from a 1 μg/m^3 reduction in sulfate air pollution.

The most significant limitation of this analysis is that it estimates the burden of disease that could be removed by practical interventions in new construction, yielding estimates of the maximum potential benefit from theoretical radon mitigation of all housing stock in 2012. Another limitation is that the percentage of radon reduction for both passive preventive measures and active depressurization systems is assumed to be independent of the initial radon level (though the absolute reduction is lower), due to insufficient data describing the rate and threshold at which the reduction would decrease. It was assumed that the relative risks of all cause and lung cancer mortality between smokers and nonsmokers derived from the US were applicable to Canada due to the similarity of the two populations.

Assessment of practical policies in Canada would require a comprehensive health economic evaluation of interventions to reduce residential radon in new and existing housing in Canada. Evaluation of the maximum potential benefit that could be derived from practical and effective radon interventions is important so that new radon remediation strategies can be identified and evaluated instead of limiting a future cost effectiveness analysis to evaluation of current radon remediation approaches. The results of this analysis suggest that active soil depressurization might be cost-effective in new construction for populations in Canada exposed to higher residential radon. The increasing proportion of the total housing stock with radon mitigation measures over time following a policy change will require modelling the rate of uptake and costs of radon mitigation retrofits for existing buildings and annual housing starts occurring after building code changes regulating radon prevention in new construction. Ongoing updating of the national radon survey by the National Radon Program, probably every 20 years or so, will measure the effect of building code changes and education and incentives to encourage mitigation of existing housing on residential radon exposures.

3.7 Conclusions

Radon is a modifiable environmental exposure in Canada that is currently the second most important cause of lung cancer after smoking. In Canada, lung cancer is the most common cause of cancer mortality for both men and women. Gains in quality-adjusted life expectancy from potential reductions in the modifiable lung cancer burden attributable to residential radon were assessed at the national, provincial and municipal levels, all of which are involved in regulating indoor air quality. A reduction in residential radon by 50% could prevent 681 annual radon-attributable lung cancer deaths, associated with a period gain of 15,445 QALYs, and a reduction by 85% could prevent 1,263 annual radon-attributable lung cancer deaths, associated with a period gain of 26,336 QALYs, for the Canadian population at a discount rate of 1.5%. Regional analyses indicate that provincial/territorial populations that would derive the greatest quality-adjusted life expectancy from radon reduction include those in the Yukon, New Brunswick, Manitoba and Saskatchewan, and the municipal populations of Sherbrooke, Regina, Winnipeg, Kelowna and Halifax.

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Chapter 4 – Overview of Health Economic Evaluation, Radon Regulations and Radon Remediation in Canada

4.1 Overview of Health Economic Evaluation

Two types of economic studies found in health care literature include analyses of the economic burden of a disease and economic evaluation of alternatives to reduce the burden of a disease. An economic evaluation can involve the comparison of a proposed intervention to standard care, or of one intervention to another. Burden of disease studies are often conducted first, to identify and quantify the cost of adverse health effects for a given population resulting from a disease or an environmental exposure. Once it has been established that a significant burden of disease exists, analysis progresses to evaluating possible interventions to reduce that burden. Economic evaluation in health care is defined as the comparison of the respective costs and consequences of alternative options and can be classified into one of three categories: cost-effectiveness analysis (CEA), cost-utility analysis (CUA), and cost-benefit analysis (CBA).

Decisions regarding resource allocation in health care can be made using CEA, CUA or CBA; which analysis is the most appropriate is determined by the variation in the health care programs under consideration. Most health care systems need to balance resource allocation across a broad range of disease areas, ranging from preventive community health programs to palliative oncology medications, and the cost-utility analysis has become the most frequently used analysis to guide health policy decisions.

Cost-effectiveness analysis is best suited for measures of health specific to a disease or intervention, such as percentage reduction in blood cholesterol for coronary heart disease, or IQ point loss for adverse neurocognitive effect. The quality adjusted life year (QALY) is the general measure of health used in the cost-utility analysis instead of the specific health measure used in a cost-effectiveness analysis. The QALY seeks to reflect both the length of life and the health-related quality of life. QALY values depend on assumptions about the nature of people's preferences for health and are often assessed using preference-based quality of life questionnaires, such as the EQ5D, the SF6D, and the HUI3. QALYs are the only generic health measure that has been widely used in a large range of clinical and community evaluations.

Cost-benefit analysis assigns a monetary value to a range of health and other consequences associated with a policy change, and therefore depends on much broader assumptions than cost-utility analysis. Contingent valuation or willingness to pay methods have been used to value health benefits in cost-benefit analysis, in which individuals estimate a hypothetical monetary payment to obtain a benefit or avoid an adverse effect. There has been reluctance to use willingness to pay methods in health care because they have been found to suffer from two serious biases: a tendency to be under-sensitive to the magnitude of benefit, and a tendency to inflate valuations of interventions that respondents are asked about compared to those that are not directly asked about (Cookson 2003).

Economic evaluation is strictly comparative, only the relative change in costs and consequences can be evaluated. Assessment of the absolute value of one configuration of resources is not possible, for example, the values for costs and consequences of standard care cannot be used as a burden of disease estimate. As long as the selection of costs and consequences included in the model are clearly stated, many different and valid models can be used to calculate a meaningful incremental cost effectiveness ratio. Treatment comparators are the alternative treatments that are compared in an economic evaluation. The reference case to which a proposed intervention is most frequently compared is usual care or standard care. The outcome or consequence considered are most often is the health-related quality of life, represented by the quality-adjusted life year (QALY), although other types of consequence relating to process such as cases found or avoided can be included. The selection of costs and consequences depends on the perspective of the analysis and the availability of reliable data.

Choices regarding which programs to fund must be made in any health care system. The use of the quality-adjusted life year enables the comparison of very different health care services and programs and comparison of programs that affect different subgroups within the population.

The cost per QALY of health interventions under consideration are assessed relative to a cost effectiveness threshold, which can be considered an estimate of how much health gains are valued in a society. The contributions from conducting cost-utility analyses include providing a clear rational basis upon which to base health program funding decisions, improving transparency and improving the effectiveness of public investment in health.

4.2 Radon Control Regulations in Canada

There are three national regulations governing radon protection in Canada: the National Building Code of Canada (NBC 2015), the Radon Guideline and the Naturally Occurring Radioactive Materials (NORM) Guidelines. All three are advisory only.

The legal requirements for the construction of new buildings are those in the respective provincial building codes, with the municipalities responsible for issuing building permits and carrying out inspections. The provincial codes generally follow the national code quite closely, with the exception of the Construction Code of Quebec, but not all provinces/territories have adopted the radon preventive sections of NBC 2015 guidelines (see Appendix B).

The Radon Guideline recommends that radon levels above 200 Bq/m^3 be mitigated, but home owners are responsible for all costs and compliance is voluntary. In 2012, the population-weighted percentage of Canadians living in homes with radon concentrations above 200 Bq/m^3 was estimated to be 6.9%, with the five provinces having the highest percentages being New Brunswick at 20.6%, the Yukon at 19.6%, Manitoba at 19.4%, Saskatchewan at 15.7%, and Nova Scotia at 10.7% (HC H144-2/2012E 2012).

The NORM guidelines apply the same radiation exposure standards for people exposed occupationally to naturally occurring radioactive materials as those applied to people exposed to other radioactive materials. Occupations in which exposure to naturally radioactive materials occur include mineral extraction and processing, and oil and gas production. However, these guidelines tend not to be applied to indoor radon exposure in other workplaces.

There are no provisions for radon testing or mitigation for rental units or workplaces, with the exception of federal workplaces that are regulated by the Canada Labour Code. The Canada Labour Code specifies that indoor radon above 800 Bq/m^3 must be mitigated, but radon monitoring is not mandatory.

The legal requirements for radon control measures to be installed during construction of new housing for each province are listed in Table 7 (see Appendix C for references and map of radon zones in BC). These measures include installation of a continuous barrier to exclude radon, provision of a rough-in for a future subfloor depressurization system, and mitigation of the housing if a radon exposure above the threshold is measured after construction.

The radon prevention measures adopted into the legally binding provincial/territorial building codes apply only to new housing and not to existing housing. The main provisions for radon protection that were first introduced into the NBC 2010 are located in part 9, for housing and small buildings, although protection from radon is also mentioned in parts 5 and 6. Subsection 9.13.4.2 of the NBC 2010 recommends the installation of an air barrier system, satisfying subsection 9.25.3, where wall, floor or roof assemblies separate a conditioned space from the ground. A conditioned space is defined as space within a building in which the temperature is controlled to limit fluctuations due to variation in ambient external or internal differential temperatures. The second provision of 9.13.4.2 is that dwelling units and buildings containing residential occupancies be provided with a rough-in for a subfloor depressurization system to extract radon conforming to 9.13.4.3 (see Appendix A), consisting of a gas-permeable layer, such as clean granular material, and a pipe venting to the exterior. These provisions have been carried forward to the current version, NBC 2015.

Table 7: Provincial building code radon protection provisions

Province (code)	**Subslab continuous air barrier**	**Subslab rough-in for radon venting**	**Radon mitigation**
Labrador and Newfoundland	NBC 2010	NBC 2010	
PEI	NBC 2010 Summerside, Charlottetown, Stratford	NBC 2010 Summerside, Charlottetown, Stratford	
Nova Scotia	NBC 2010	NBC 2010	
New Brunswick NBC enacted but not yet in force for all of province	NBC 2010 Moncton, Fredericton and Bathurst	NBC 2010 Moncton, Fredericton and Bathurst	
Quebec **(9.13.2.7** **-eff 17/05/08)** **A-9.13.2.1. 3** **A-9.13.4.1. 1**	Advisory only Required where radon proven to be a problem (Oka) Required for floors-on-ground, and masonry walls and floors	if radon during construction is >800 Bq/m3 where radon proven to be a problem	for single dwellings >800 Bq/m3 after construction where radon proven to be a problem
Ontario **(9.13.4, 9.1.17** **- Eff 19/12/14)** **9.25.3**	Only where methane or radon gases known to be a problem Allows for foundation walls, floor slab, and vapour barriers to be used as an air barrier (SB-9)		for single dwellings >250 Bq/m3 in 3 regions (Elliot Lake, townships of Faraday & Hyman
Manitoba	NBC 2010	NBC 2010	
Saskatchewan	NBC 2010	NBC 2010	
Alberta	No	no	
British Columbia **(9.13.4.1, 9.13.4.2 and 9.13.4.3** **- Effective 19/12/14)** **9.25.3**	Polyethylene soil gas barrier required where conditioned space is separated from unconditioned space or the ground, except where radon known not to be a problem (area 2, see App. B)	NBC 2010 in radon prone area (Area 1, App. C)	Full passive stack required during construction in radon prone area (Area 1, App. C)
Nunavut	No	no	
Northwest Territories	NBC 2010	NBC 2010	
Yukon	NBC 2010	NBC 2010	

4.3 Approach to Improving Radon Control in Canada

Regulatory approaches for reducing residential radon were assessed for British Columbia in 2012 by Jeff Miller, at the Environmental Law Clinic at the University of Victoria (Miller 2012). Four pillars were adapted to the Canadian context from the WHO Handbook on Indoor Radon framework (World Health Organization 2009).

The four adapted pillars are presented below:

1) Proactive prevention of radon gas incursion into the interior of residential structures
2) Testing for radon gas in existing structures
3) Remediation of indoor radon gas concentrations in excess of prescribed threshold
4) Public education

The first strategy is achieved by changing the building code that regulates construction of new buildings. Recommendation 6 in the recent review of policy and law in Canada regarding radon in indoor air encourages provincial/territorial governments to adopt the radon protection and mitigation provisions described in the NBC, 2010, into their respective building codes (Dunn and Cooper 2014).

Radon exposure in existing buildings is generally addressed by one of three approaches: regulation requiring radon testing and mitigation above threshold at point of sale, tax credit, or direct subsidy. Public education is important whether incentives or legislation are used to increase the frequency of radon testing and mitigation.

Regulation at point of sale appears to mirror existing point of sale regulation concerning toxic building materials, but no country or state has implemented point of sale regulation. Resistance to mandatory point of sale testing poses challenges, because reliable radon measurement depends on long-term measurement (minimum 3 months) conducted during the winter months. A hold-back could theoretically be used, but the Canadian Real Estate Association has strongly resisted point of sale radon measurement in the past. Further disadvantages concerning enforcement of point of sale regulation, under contract law, are described in detail in the review of policy and law in Canada regarding radon in indoor air published by the Canadian Environmental Law Association (Dunn and Cooper 2014).

The review of policy and law in Canada regarding radon in indoor air noted the divided and overlapping jurisdiction regarding regulation of indoor air in Canada. Only national implementation of a federal government policy could provide a broad and consistent approach (Dunn and Cooper 2014). However, the economic benefits of reducing radon attributable lung cancer cases are accrued by the health care system, which is administered at the provincial/territorial level. Direct partial subsidies have proved a successful approach for low incomes in Maine, in the US (Miller 2012). Direct full or partial subsidies can be more equitable, but low income individuals are less likely to be home owners. Tax credits and direct subsidies both have the advantage that the home owner who is incurring the cost of radon testing and mitigation is also the beneficiary of the reductions in residential radon.

A voluntary strategy is deemed most likely to be successful in Canada, based on encouraging home owners to test and mitigate radon levels over a mitigation threshold. A federal policy of radon remediation tax credits would offer benefit nationwide and could be implemented quickly, without the need for negotiation among many different provinces and municipalities. Incentives have led to widespread adoption of new policies when compared to mandatory measures, which can be interpreted as punitive, and a successful example in Canada was the tax credit offered under the ecoEnergy retrofit – homes program (Natural Resources Canada 2014).

In Europe, the Council of the European Union recently issued a new regulation limiting exposure to radiation that includes residential radon exposure for the first time in the radiological protection system. The EURATOM Basic Safety Standards (BSS) 59/2013 was implemented in February 2018 and establishes a reference level of 300 Bq/m^3 (Gutierrez-Villaneuva 2018). However, the national radon action plans for most of the EU countries have yet to be developed and it will be interesting to review approaches used to implement this directive.

4.4 Investment in Preventive Health Interventions in Canada

The Public Health Agency of Canada promotes investment in preventive health interventions, many of which are cost effective and some are even cost-saving (Public Health Agency of Canada 2009). Preventive health interventions include clinical prevention and health promotion delivered at the individual level, and health protection and healthy public policies that reduce health risks by changing the physical or social environment at the population level.

Indirect costs are included when a cost-utility analysis adopts a societal perspective, and the Public Health Agency of Canada recommends that more cost-utility analyses be conducted in Canada and that a societal perspective be adopted more frequently (Public Health Agency of Canada 2009). A recent review of health care decision making in Canada noted that cost-utility analyses are included much less frequently in Canada than in the UK, and concluded that it would be beneficial if cost-utility analyses were conducted more often in Canada (Jaswal 2013). While the costs of reducing residential radon exposure fall outside the health care system, the costs associated with treating radon attributable lung cancer cases are substantial; the average annual costs of lung cancer care in Canada in 2012 were estimated to be 7.5 billion dollars, adjusted to 2015 Canadian dollars (de Oliveira et al. 2018). Interventions to reduce residential radon exposures in Canada constitute a health protection intervention worth evaluating using a cost-utility analysis.

4.5 Cost-utility Analysis of Residential Radon Interventions in Canada

Estimates of the incremental cost effectiveness ratio for practical residential radon interventions would help policy-makers to invest limited health care resources rationally, balancing funding between increasingly expensive new chemotherapy drugs for lung cancer treatment with lung cancer prevention. Future lung cancer treatment costs would be reduced by current investment into practical interventions to reduce residential radon exposure.

Cost-utility analyses for practical radon interventions in Canada to reduce residential radon exposures in new and existing housing are described in the next two chapters. The analyses are conducted according to the fourth edition of the Guidelines for the Economic Evaluation of Health Technologies, Canada (Canadian Agency for Drugs and Technologies in Health 2017). The treatment comparators are listed below:

1. No specific radon control measures in new or existing housing.
2. Passive preventive radon measures installed in new housing at construction, with or without activation for above mitigation threshold radon after construction.
3. Active depressurization system in all new housing regardless of radon exposure.
4. The combination of activation of passive preventive measures in new housing and retrofit for an active depressurization system in existing housing for above mitigation threshold radon exposures in both new and existing housing.
5. The combination of an activation depressurization system in all new housing and, at above mitigation threshold radon exposures in existing housing, retrofit for an active depressurization system in existing housing.
6. Screening and mitigation of existing housing at above mitigation threshold radon exposures.

The treatment comparators are evaluated for each of three mitigation thresholds, at 200, 100 and 50 Bq/m^3, and at two rates of testing and mitigation, the current low rates and increased rates under a theoretical tax credit incentive. Two reference cases are used for the analyses included in this economic evaluation: first, no specific radon control measures in housing; and second, the passive preventive measures described in the National Building Code 2015 that are installed in new housing at construction and have been adopted in most provinces/territories. The outcomes include QALYs and radon attributable lung cancer deaths, with this analysis restricted to the assessment of lung cancer mortality. It is conducted from a societal perspective and so it includes the costs associated with reducing radon exposures in housing. The costs include radon testing, the installation of passive preventive measures in new housing at construction, retrofits of active depressurization systems in existing housing, and maintenance costs for active depressurization systems. Detailed descriptions of the cost-utility analyses are described in Chapters 5 and 6, and the results are summarized and the implications are discussed in the final chapter.

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Chapter 5 - Cost-utility analysis of practical radon interventions in Canada, the provinces/territories, and 17 CMAs

5.1 Abstract

The objective of this analysis is to estimate the incremental cost utility ratios and the annual number of lung cancer deaths prevented for the 2012 populations in Canada, each province/territory and 17 census metropolitan areas, for practical radon mitigation scenarios to reduce residential radon exposures. Sixteen intervention scenarios compare radon mitigation implemented at differing rates in new and existing housing relative to preventive measures installed at construction, using three different radon thresholds. A period life-table analysis was conducted using data derived from two recent Canadian radon surveys, along with Canadian mortality and quality of life data. Analyses adopted a lifetime horizon and a discount rate of 1.5%. The most cost effective radon intervention scenario for all target populations is the combination of the activation of the preventive measures in new housing and mitigation of existing housing at above threshold radon. It is practical and cost effective to reduce residential radon and associated burden from lung cancer mortality in many regions in Canada.

5.2 Background

Radon is an important and modifiable cause of lung cancer, second only to smoking, that was first identified as a human carcinogen by the International Agency for Research on Cancer (IARC) in 1988 (Dunn and Cooper 2014). Following inhalation of naturally occurring radon gas and some short-lived radon progeny, the alpha particles emitted in radioactive decay can damage cellular DNA in the lung tissue. Radon is produced when uranium-238 in the ground undergoes radioactive decay, and can collect in houses after entering from the surrounding soil via various entry points (such as cracks in concrete and gaps around service pipes). The most cost-effective method of reducing residential radon exposure is to install preventive measures during construction of new buildings (Gray et al. 2009).

Cancer is estimated to account for one quarter of mortality in Canada, with lung cancer representing the highest number of cancer deaths at 27% for men and women combined (Canadian Cancer Society et al. 2014). The population attributable risk of lung cancer for residential radon in Canada has recently been estimated to be 16% (Chen et al. 2012). In 2011, the annual economic burden from lung cancer in Canada was estimated to $398,000,000 (Dunn and Cooper 2014).

The voluntary radon Guideline recommends that homeowners mitigate when residential radon levels exceed 200 Bq/m^3, and it was estimated in 2012 that 6.9% of Canadians were living in homes with above mitigation threshold radon exposures (Health Canada 2012). The highest percentage of residents exposed to above threshold radon at the provincial level include New Brunswick at 20.6%, the Yukon at 19.6%, Manitoba at 19.4%, Saskatchewan at 15.7%.

Government jurisdiction at the federal, provincial and municipal levels intersect over radon in indoor air because areas of health and the environment in Canada have been determined by the courts to be under shared jurisdiction (Dunn and Cooper 2014). Prevention of radon ingress into new housing can be achieved through building code changes, while approaches that have been proposed for reducing radon exposures in existing housing include a tax credit, a direct subsidy or regulation at point of sale. Public education is important whether incentives or legislation are used to enable radon testing and mitigation.

Radon control in new housing is addressed in the National Building Code of Canada, a federal model code that may be adopted by the provinces/territories, though regulation of indoor air quality occurs at provincial and municipal levels. Revisions made in 2010 to the National Building Code (NBC) of Canada for radon control in new homes included a rough-in requirement for a future radon removal system and enhanced sealing of possible radon entry points including the use of a radon membrane under the foundation slab (Dunn and Cooper 2014).

A federal policy of radon remediation tax credits for existing housing would offer uniform benefit nationwide and could be implemented quickly, without the need for negotiation among many different provinces and municipalities. The Green Budget Coalition recommendations for 2016 and for 2018 proposed a federal tax credit for radon remediation, suggesting that the investment required would be negligible or even have a positive net tax impact because reduced income tax revenues would be offset by increased tax revenue from radon mitigation businesses (Cooper 2016; Green Budget Coalition 2015, 2017). It was also estimated that $17 million dollars in annual lung cancer treatment costs would be saved if homes with radon levels above 200 Bq/m^3 were mitigated. Direct subsidies for radon mitigation have been successful in high radon areas in several US states: Illinois, Maine and Iowa (Bain et al. 2016; Miller 2012). Disadvantages of point of sale regulation, under contract law, are described in detail in the review of policy and law in Canada regarding radon in indoor air published by the Canadian Environmental Law Association (Dunn and Cooper 2014). Resistance to mandatory point of sale testing poses challenges because reliable radon assessment depends on long-term measurement (minimum 3 months) during the winter months.

A cost-utility analysis is conducted to assess the impact of 16 radon mitigation scenarios over a hundred-year period in Canada. Quality-adjusted life years (QALYs) are used to represent the health gain, as recommended in the 4th edition of the CADTH Guidelines for the Economic Evaluation of Health Technologies: Canada (Canadian Agency for Drugs and Technologies in Health 2017). This model represents the gradual conversion of the housing stock to universal radon prevention through the implementation of practical interventions over time to reduce residential radon exposure and associated health effects in the Canadian population over age, smoking status and sex specific categories, both nationally and provincially. The practical interventions most likely to be adopted in Canada were selected for new and existing housing. Building code changes in most provinces already require measures to prevent radon incursion into new housing. A tax credit incentive for mitigation of existing housing is included in this model due to the success of the ecoEnergy Retrofit Homes Program (Natural Resources Canada 2014), a federal tax credit incentive that proved very successful in Canada between 2008 and 2012 to encourage homeowners to improve the energy efficiency of their homes.

5.3 Research Question

The objective of this analysis is to estimate the incremental cost utility ratios and the annual number of lung cancer deaths prevented for the 2012 populations in Canada, each province/territory and 17 census metropolitan areas, for practical radon mitigation scenarios to reduce residential radon exposures. The health care system and society generally in Canada shoulder the health and economic burden from radon associated lung cancer. Investment of limited health care resources into preventive radon reduction interventions in Canada would reduce lung cancer treatment costs in the future. Determining which interventions are cost effective can aid policy-makers balancing funding between increasingly expensive new chemotherapy drugs for lung cancer treatment with lung cancer prevention via radon reduction interventions. The Radiation Protection Bureau developed and implemented the National Radon Program starting in 2007 based on a preceeding consultation with Federal/Provincial/Territorial partners to provide expertise in areas ranging from radon research and testing to radon education and public awareness strategies. Decision makers who could be coordinated by the Radiation Protection Bureau to implement new radon reduction initiatives might include the provincial health authorities, the provincial housing authorities (regarding the provincial building codes), municipal housing authorities who enforce building codes and issue permits, and federal departments involved in shaping the national budget should tax incentives be considered.

5.4 Methods

5.4.1 Target populations

Analysis was conducted for both national and provincial/territorial populations based initially on the 2012 Canadian population modelled with replacement over the 100 year period of the analysis (Statistics Canada 2012b). In addition, the populations of the following 17 CMAs were modelled, being derived from the 2011 Census data (Statistics Canada 2011a): St. John's (NL), Halifax (NS), St. John (NB), Quebec (QC), Sherbrooke (QC), Montreal (QC), Ottawa-Gatineau (NCR), Kingston (ON), Toronto (ON), Windsor (ON), Winnipeg (MB), Saskatoon (SK), Regina (SK), Edmonton (AB), Calgary (AB), Kelowna (BC), and Vancouver (BC). The census data used to model population growth was averaged from 2006-2016.

5.4.2 Intervention strategies

The radon control measures modelled include regulation requiring installation of radon prevention measures in new construction (passive and active), with retesting of radon levels in subsequently mitigated housing every 5 years and in below threshold housing every 10 years, testing and mitigation of existing housing at current rates, and a tax credit incentive to promote mitigation of existing housing with above threshold radon exposure. Radon testing rates were assumed to rise quickly, and mitigation rates for above threshold homes were assumed to increase quickly amongst home owners willing to test, reaching ninety percent 20 years after the implementation of the tax credit incentive. Three radon mitigation thresholds were considered: 200 Bq/m^3, 100 Bq/m^3, and 50 Bq/m^3. The intervention scenarios described below are summarized in Table 8. The current radon testing and mitigation rates along with the theoretical effect of the tax credit incentive over the time horizon are shown in Figure 5.

<u>Radon Intervention Scenarios for Canada</u>

Scenario PN – Baseline option requiring the passive preventive measures described in the 2015 National Building Code of Canada to be installed in all new housing.

Scenarios PN T200AN, PN T100AN, PN T50AN – Passive preventive measures installed in new housing, for above threshold radon (T200, T100, T50) active depressurization system in new housing.

Scenario AN – Maximize radon prevention in new housing, building code change requiring active depressurization system in new housing.

Scenarios AN T200RE, AN T100RE, AN T50RE – Active depressurization system in new housing and, for above threshold radon levels, retrofit of existing housing with active depressurization system.

Scenarios AN T200CRE, AN T100CRE, AN T50CRE – Active depressurization system in new housing and, for above threshold radon levels, tax credit incentive for retrofit of existing housing with active depressurization system.

Scenarios PN T200ANRE, PN T100ANRE, PN T50ANRE –Passive preventive measures in new housing and, at above threshold radon levels, active depressurization system in new housing and from retrofit of existing housing.

Scenarios PN T200ANCRE, PN T100ANCRE, PN T50ANCRE – Passive preventive measures in new housing and, at above threshold radon levels, active depressurization system in new housing and with tax credit incentive for retrofit of existing housing

Scenario PN is the baseline for the health economic evaluation of practical interventions to reduce residential radon in Canada, consisting of passive radon prevention measures installed at construction. Scenarios PN T200AN, PN T100AN, PN T50AN extend the baseline requirement for new construction to include radon testing and active depressurization in new housing found to have above threshold radon levels after construction. Three radon thresholds are modelled: 200 Bq/m^3 (the current Canadian guideline), 100 Bq/m^3 (the WHO recommended guideline), and 50 Bq/m^3. The cost-effectiveness of the baseline and extended baseline scenarios are estimated relative to no specific radon control measures installed during construction. Most provinces and territories in Canada already require a radon membrane and a rough-in for a depressurization system for new housing. Therefore, a sequential analysis is conducted for the remaining scenarios, with the cost-effectiveness estimated relative to the baseline, scenario PN, in the first stage, and at subsequent stages, relative to the most cost-effective scenario identified in the previous stage.

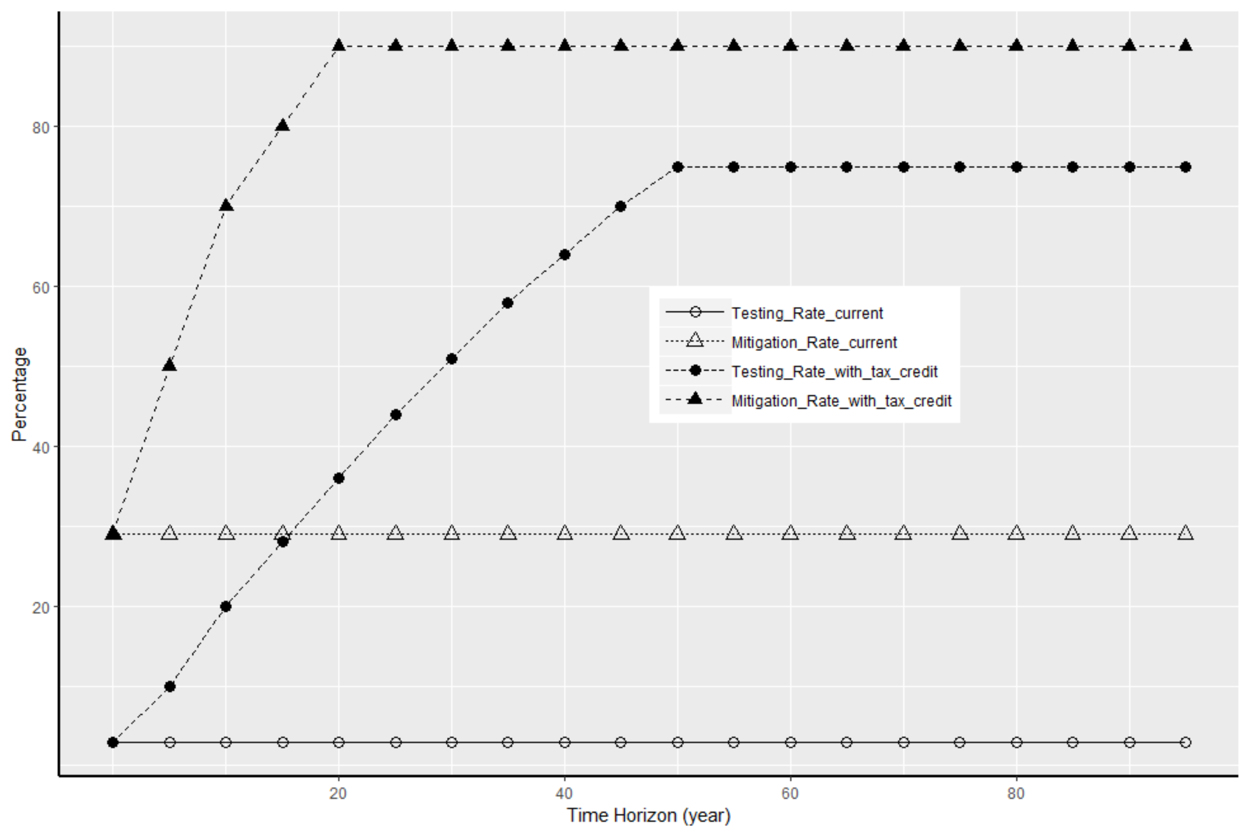

Figure 5: Radon testing and mitigation rates at current levels and with a tax credit incentive

(same information as Figure 4 in Chapter 3)

Table 8: Radon intervention scenarios

Scenario (PN, AN, RE) Threshold (T)	New Construction		Existing Housing		Notes
	Rn test	**Radon prevention**	**Rn test**	**Retrofit**	
PN	×	Passive	×	×	**P**assive preventive measures in **N**ew construction only
PN T200AN	✓	Passive/Active	×	×	**P**assive preventive measures in **N**ew construction, At Rn>200 Bq/m3: **A**ctivated depressurization in **N**ew construction
PN T100AN	✓	Passive/Active	×	×	**P**assive preventive measures in **N**ew construction, At Rn>100 Bq/m3: **A**ctivated depressurization in **N**ew construction
PN T50AN	✓	Passive/Active	×	×	**P**assive preventive measures in **N**ew construction, At Rn>50 Bq/m3: **A**ctivated depressurization in **N**ew construction
AN	✓	Active	×	×	**A**ctivated depressurization in **N**ew construction only
AN T200RE	✓	Active	✓	✓	**A**ctivated depressurization in **N**ew construction At Rn>200 Bq/m3: **R**etrofit for activated depressurization of **E**xisting housing
AN T100RE	✓	Active	✓	✓	**A**ctivated depressurization in **N**ew construction At Rn>100 Bq/m3: **R**etrofit for activated depressurization of **E**xisting housing
AN T50RE	✓	Active	✓	✓	**A**ctivated depressurization in **N**ew construction At Rn>50 Bq/m3: **R**etrofit for activated depressurization of **E**xisting housing
AN T200CRE	✓	Active	✓	✓	**A**ctivated depressurization in **N**ew construction At Rn>200 Bq/m3: **C**redit for **R**etrofit foractivated depressurization of **E**xisting housing
AN T100CRE	✓	Active	✓	✓	**A**ctivated depressurization in **N**ew construction At Rn>100 Bq/m3: **C**redit for **R**etrofit foractivated depressurization of **E**xisting housing
AN T50CRE	✓	Active	✓	✓	**A**ctivated depressurization in **N**ew construction At Rn>50 Bq/m3: **C**redit for **R**etrofit foractivated depressurization of **E**xisting housing

Scenario (PN, AN, RE) Threshold (T)	New Construction		Existing Housing		Notes
	Rn test	Radon prevention	Rn test	Retrofit	
PN T200ANRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>200 Bq/m3: **A**ctivated depressurization in **N**ew construction & **R**etrofit for activated depressurization of **E**xisting housing
PN T100ANRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>100 Bq/m3: **A**ctivated depressurization in **N**ew construction & **R**etrofit for activated depressurization of **E**xisting housing
PN T50ANRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>50 Bq/m3: **A**ctivated depressurization in **N**ew construction & **R**etrofit for activated depressurization of **E**xisting housing
PN T200ANCRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>200 Bq/m3: **A**ctivated depressurization in **N**ew construction & **C**redit for **R**etrofit for activated depressurization of **E**xisting housing
PN T100ANCRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>100 Bq/m3: **A**ctivated depressurization in **N**ew construction & **C**redit for **R**etrofit for activated depressurization of **E**xisting housing
PN T50ANCRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>50 Bq/m3: **A**ctivated depressurization in **N**ew construction & **C**redit for **R**etrofit for activated depressurization of **E**xisting housing

5.4.3 Study perspective and time horizon

A societal perspective was adopted because reduction of residential radon exposure and associated costs occur outside the health care system, and a hundred year time horizon because residential radon exposure is lifelong, lung cancer mortality in Canada peaks between age 75 and 89 years, and the benefits of radon reduction are experienced by all current and future residents of the remediated housing.

5.4.4 Discounting

The discount rate used for the base analysis is 1.5%, recommended by the Canadian Agency for Drugs and Technologies in Health (CADTH 2017). A discount rate of 0% is also used for comparison purposes.

5.4.5 Modelling

The gradual conversion of housing to include radon control over the time horizon is represented by an increasing proportion of the housing stock having the practical radon interventions specified in each scenario. This model assumes the measured residential radon exposure exists until the time that a specific radon control measure is introduced to reduce that exposure. The housing model uses 5 year intervals, with housing stock growth, new construction incorporating preventive radon measures, and radon testing and subsequent mitigation of a proportion of the existing housing occurring during each interval. The 2011 values and growth rates averaged from 2007-2017 data were applied over the time horizon, to avoid any projections concerning changes in demographics or housing stock.

The abridged period life-table approach uses 5 year age intervals, and age-and sex-specific all cause and lung cancer probabilities of death from the census and death databases. The mortality rate is used as the hazard rate to calculate the probability of surviving to the end of each 5 year interval. The probability of dying during that interval is one minus the probability of surviving. The probabilities of death reported in the death database were converted into mortality rates. An exposed person’s risk is modelled as the sum of the baseline risk and the risk due to radon exposure. The ERR model of lung cancer mortality used in this analysis is based on lifetime radon exposure, assessed for each age-group in the population, and incorporating the timing and the reductions in radon exposures from the interventions described in the housing model. The baseline and radon exposed life expectancy (LE, LE_E) and lifetime risk (LR, LR_E) of lung cancer are evaluated using the probability of surviving to the beginning of each age interval, of dying during the age interval, from the intensity ratio between all cause and lung cancer mortality, and the population growth over the time horizon. The number of lung cancer death attributable to radon is determined from the population attributable risk, calculated in equation 1 from the population-averaged lifetime risk in the exposed population (LR_E) and the baseline lifetime risk for a theoretical unexposed population (LR) as described in Brand et al. (2005):

$$PAR = \frac{LR_E - LR}{LR_E} \qquad (Eq\ 1)$$

5.4.6 Residential radon distribution

Representative residential radon distributions, defined by the geometric mean and the geometric standard deviation, for Canada, the provinces/territories, and 17 Census Metropolitan Areas (CMAs) are listed in Table 9. The fitdistplus function in the programming language R using population weights and the maximum likelihood estimator were used to determine the radon distributions from two recent Canadian radon surveys conducted by the Radiation Protection Bureau, Health Canada: national and provincial/territorial distributions from a representative national radon survey conducted between 2009-2011 (Health Canada 2012) and distributions for CMAs from a radon-thoron survey of 33 CMAs in Canada conducted in 2012-2013 (Chen et al. 2015). The national radon survey was based on 3 month-long indoor measurements taken during the winter months using passive alpha-track radon detectors from Track Analysis Systems Limited (TASL). The sampling strategy used stratified random sampling of all Health Regions in Canada, defined as geographic administrative areas of responsibility for a hospital board or regional health authority. Seventy-six percent of the 18,000 participants recruited from the 121 Health Regions returned valid results, yielding 13,814 radon levels. The radon-thoron survey of 33 Census Metropolitan Areas (CMAs) in Canada assessed radon exposure in roughly 4000 homes yielded 3188 valid radon results, measured using passive radon-thoron discriminative track detectors (RADUET - Radosys Ltd). Residential radon data below the detection limit of 15 Bq/m^3 were approximated in this analysis by half that value, 7.5 Bq/m^3.

Measured radon distributions are subject to uncertainty from the year-to-year variation that has been reported from residential radon studies incorporating repeated annual measurement in a subset of dwellings (Darby et al. 1998, 2006b). In this analysis, a correction is made to the variance of the distribution fitted to the measured radon levels by subtracting the year-to-year variation using the method described in Darby et al. (2006) and Gray et al. (Gray et al. 2009). It is assumed that the year-to-year variation follows a lognormal distribution about the true radon concentration and is independent of the magnitude of the radon concentration. The year-to-year variation is estimated from the difference for the 33 CMAs between the 2009-2011 national survey and the 2012-2013 CMA survey.

5.4.7 Housing Model

The 2011 CMHC data was used to model new construction (CMHC) and housing stock (Statistics Canada 2011b). A portion of the new construction will house the growth in population, while some will contribute to the replacement of older housing stock. A model representing dwellings occupied by usual residents was considered appropriate for calculating the residential radon exposures of the population (Table 10). Ten years of data was averaged to model the number and growth rate for housing stock and new construction to smooth out annual fluctuations, with demolitions assumed to make up the difference for dwellings occupied by usual residents between new construction and housing stock growth (ie housing renewal). Demolition data has not been collected by Statistics Canada since the year 1999, and the contribution from conversions is relatively small. Annual fluctuations in vacancy rate and completion rate of new housing construction (new starts or house starts) tend to form a balance when modelling total housing stock, but were not considered necessary for this model based on 10-year averages and limited to dwellings occupied by usual residents. Rental properties are not considered separately although landlords are not currently required to test or mitigate radon exposure to tenants. Most renters on upper floors of apartment buildings are not likely to be exposed to high radon levels. This model is based on the extrapolation over the 100-year time horizon of the data averaged between 2007 and 2016 for housing stock and new house starts.

Table 9: Radon distribution for Canada, provinces, and census metropolitan areas

Canada, Provinces, Territories	**Radon Distribution**		***CMA***	**Radon Distribution**	
	Geometric Mean	**Geometric SD**		**Geometric Mean**	**Geometric SD**
Canada	41.7	2.64			
NL	32.8	2.94	*St. John's, NL*	62.5	2.34
NS	38.6	3.34	*Halifax, NS*	91.3	3.14
PEI	22.3	2.71			
NB	62.4	3.55	*St. John, NB*	70.8	2.74
QC	36.6	3.04	*Quebec City, QC*	67.4	2.74
			Sherbrooke, QC	119.8	2.64
			Montreal, QC	69.4	2.54
ON	34.4	2.64	*Ottawa-Gat, CR*	79.1	2.13
			Kingston, ON	123.2	2.03
			Toronto, ON	45.3	1.82
			Windsor, ON	122.5	1.72
MB	100.1	2.38	*Winnipeg, MB*	198.9	1.93
SK	88.0	2.23	*Saskatoon, SK*	138.5	1.38
			Regina, SK	240.8	1.93
AB	64.6	1.99	*Edmonton, AB*	96.2	1.72
			Calgary, AB	106.8	1.72
BC	25.5	2.06	*Kelowna, BC*	96.7	1.93
			Vancouver, BC	20.9	1.93
NU	8.60	1.19			
NT	39.4	2.93			
YT	85.7	2.88			

(same information as Table 3 in Chapter 3)

5.4.8 All Cause and Lung Cancer Mortality by Smoking Status

Current smoking data for 2012 was used in this analysis (Table 11), reported nationally and for each province and territory by the Canadian Community Health Survey (CCHS) according to sex- and age-specific category (Statistics Canada 2012b). All-cause mortality rates for 2012 were reported in the Death Database (Statistics Canada 2012a), by sex- and age-specific category in Canada, nationally and for each province and territory. Lung cancer mortality rates were assumed to constitute the same proportion of lung cancer incidence rates (Statistics Canada 2012c) as were reported in the National Cancer Institute Surveillance Epidemiological and End Results (SEER) cancer statistics review for the US population between 1975 and 2009 (Howlader et al. 2012), based on similar patterns of high mortality rates and low life expectancy post diagnosis in both countries. All-cause and lung cancer mortality rates were adjusted for smoking using the respective relative risk for smokers versus nonsmokers by sex- and age-specific category (Villeneuve and Mao 1994). This analysis used the values reported by the American Cancer Society Cancer Prevention Study II (ACS CPS-II) for relative risk of all cause and lung cancer mortality for smokers versus nonsmokers (RR_e) by sex and age category (Thun et al. 1997). The CPS II relative risk for current (daily and occasional) versus lifelong nonsmokers by age and sex category are given in Table 4. Former smokers in the population were modelled according to time since quitting, based on recent research estimating the relative risk of former smokers (Kenfield et al. 2008; Pesch et al. 2012). In this analysis smokers who quit more than 20 years prior were modelled as lifelong nonsmokers, and a linear decrease in relative risk (from lifetime smoker to lifetime nonsmoker) over a 20 year period was applied to former smokers. Ten- year averages for the all-cause and lung cancer mortality rates, from 2003-2012, were used for the Yukon, the Northwest Territories and Nunavut due to the small population sizes in the territories.

Table 10:Housing characteristics and population growth for Canada, provinces, and census metropolitan areas

Canada, Provinces	**Private Dwellings occupied by usual residents**			**Housing exposed to radon %**	**Pop Growth %**
CMAs	**Housing Stock 2011**	**Housing Stock Growth %**	**House Starts %**		
Canada	13,320,614	6.143	6.718	86.7	5.597
NL	208,842	5.130	5.598	96.9	1.409
St. John's	78,954	7.677	9.298	95.3	10.033
NS	390,279	3.223	4.547	88.2	0.555
Halifax	165,153	5.029	6.632	78.7	7.109
PEI	56,462	5.657	6.409	93.2	2.597
NB	314,007	3.806	4.569	92.2	1.172
St. John	52,769	0.195	3.872	87.0	2.108
QC	3,395,343	5.050	5.974	78.8	4.096
Quebec City	346,578	4.418	7.468	75.5	6.122
Sherbrooke	91,252	4.740	7.334	77.6	6.317
Montreal	1,659,161	4.107	5.753	71.0	6.302
ON	4,887,508	6.291	6.792	78.7	5.297
Ottawa-Gat (NCR)	505,769	5.878	5.949	78.7	9.593
Kingston	65,965	2.956	4.989	80.7	6.240
Toronto	1,989,705	7.348	8.711	67.3	11.041
Windsor	126,843	4.785	4.785	86.3	2.619
MB	466,138	4.321	5.770	85.3	5.658
Winnipeg	291,316	5.229	5.981	79.7	8.436
SK	409,645	5.549	7.174	90.9	6.724
Saskatoon	104,814	9.988	11.706	85.0	17.362

Canada, Provinces	Private Dwellings occupied by usual residents			Housing exposed to radon %	Pop Growth %
CMAs	Housing Stock 2011	Housing Stock Growth %	House Starts %		
Regina	86,060	10.336	10.657	87.0	13.400
AB	1,390,275	9.764	10.711	88.8	11.805
Edmonton	464,001	12.003	12.456	86.7	18.069
Calgary	450,787	11.393	11.887	85.0	17.279
BC	1,764,637	6.779	7.676	78.2	6.498
Kelowna	74,942	8.595	9.505	88.5	11.101
Vancouver	891,336	7.804	9.871	72.7	10.209
NU	14,117	9.209	11.388	93.4	9.058
NT	14,700	2.575	3.588	89.9	0.388
YT	8,661	11.338	9.209	94.2	10.976

Table 11: Age-specific HUI, and age- and sex-specific relative risk for all-cause and lung cancer mortality

Age-Group (years)	**HUI Mean (sd)**	**RR all-cause mortality M**	**RR all-cause mortality F**	**RR lung cancer mortality M**	**RR lung cancer mortality F**	**Canada: current smoker, daily or occasional M Mean (95% CI)**	**Canada: current smoker, daily or occasional F Mean (95% CI)**
0-4	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
5-9	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
10-14	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
15-19	0.896 (0.154)	1.0	1.0	1.0	1.0	9.5 (7.8, 11.1)	8.9 (7.3, 10.5)
20-24	0.905 (0.158)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
25-29	0.909 (0.159)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
30-34	0.909 (0.160)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
35-39	0.907 (0.164)	3.0	1.1	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
40-44	0.883 (0.195)	3.2	1.0	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
45-49	0.862 (0.209)	2.8	2.1	7.0	22.1	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
50-54	0.846 (0.221)	3.1	1.9	21.1	11.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
55-59	0.841 (0.219)	3.0	2.2	39.0	16.6	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
60-64	0.846 (0.213)	2.7	2.3	31.3	14.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
65-69	0.846 (0.210)	2.6	2.3	27.0	17.1	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
70-74	0.825 (0.221)	2.5	2.1	26.0	10.2	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
75-79	0.796 (0.243)	2.1	1.9	21.5	12.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
80-84	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
85-89	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
90-94	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
95-99	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)

(same information as Table 4 in Chapter 3)

5.4.9 Excess Relative Risk Model for lung cancer mortality from radon exposure

The BEIR VI exposure-age-concentration (EAC) model (NRC 1999) based on 11 miner cohorts, including more than one million person-years of observation, is the most comprehensive radon risk projection model. This model estimates the ERR per Working Level Month (ERR/WLM) in relation to cumulative radon exposure, including modifying factors for smoking status, effective exposure duration, attained age and exposure-rate effect. The smoking adjustment factor for nonsmokers is roughly double that for smokers, the attained age factor decreases with age over 55 years, and the exposure-rate factor decreases with exposure rate over 0.5 WLM. The effective exposure duration (η_t) is calculated using three weighted periods, assuming a 5 year latency period, and can therefore incorporate changes in radon exposure rate over the modelled lifetime (Equation 2):

$$\eta_t = \Delta_{[5,14]}(t) + \theta_2 \Delta_{[15,24]}(t) + \theta_3 \Delta_{[25+]}(t) \qquad (2)$$

And $\Delta_{[a,b]}(t)$ = {10 for $t > b$; (t-a) for $a \le t \le b$; 0 otherwise}

Central estimates of the parameter values for the modifying factors (derived from an overall fit of the EAC model to 11 miner cohort studies taken from Krewski et al. (1999) were described in greater detail in Brand et al. (2005). The residential radon exposure in Bq/m^3 is converted into Working Level Months for use in the miner ERR models, and assuming an equilibrium factor of 0.4 and 7000 hours per year indoors at home leads to 1 Bq/m3 radon exposure for 1 year equalling 0.0044 WLM at home.

5.4.10 Effectiveness

Passive protective measures to reduce residential radon in new construction typically yield about a 50% reduction in radon levels. Active soil depressurization draws radon-containing soil gas from beneath the slab and exhaust it outdoors and typically results in about an 85% reduction in high radon levels.

5.4.11 Quality of Life

Health related quality of life is characterized using the age-specific values (Table 9) for Health Utilities Index Mark 3 (HUI3) reported in the Canadian Community Health Survey (CCHS) for 2009-10 (Statistics Canada 2010). The change in quality of life is assessed only in terms of mortality (the disutility due to lung cancer morbidity is not included) and will likely lead to results that are conservative.

5.4.12 Costs

The distributions of costs of radon testing and mitigation measures are assumed to be constant over the 100 year time horizon and are listed in Table 12. Estimates of current construction costs for radon mitigation are used for the entire time horizon, which is conservative because these would be expected to continue to decrease with increasing uptake of radon mitigation.

Table 12: Costs of radon control measures

Radon Control Measure	**Cost**	
	mean	standard deviation
Radon test	$30	
New Construction passive preventive measures	$250	$20
New Construction active stack	$900	$30
Retrofit active stack	$1,800	$60
Maintenance for active stack (5 yrs)	$255	$15

5.4.13 Analysis

The incremental cost effectiveness ratio (ICER) for the baseline and extended baseline scenarios compared to no radon control measures are estimated in this analysis because Ontario and Quebec have not yet universally adopted the 2015 NBC radon ingress provisions for new construction.

A sequential analysis is conducted for all target populations for the intervention scenarios that combine mitigation in new and existing housing relative to the baseline preventive measures installed at construction. Two combinations of radon control measures that include mitigation of above threshold in existing housing are evaluated, with an active soil depressurization system in above threshold new housing only and also in all new housing. Mitigation of above threshold radon in existing housing is modelled using the current voluntary basis and at a significantly higher rate that could result from an incentive program such as a government tax credit. Active soil depressurization system in all new housing is also assessed.

In the first stage of the sequential analysis conducted for all target populations, the ICERs relative to the baseline, scenario PN, are estimated and ranked in order of increasing costs (for each radon threshold). The scenario with the lowest ICER indicates the intervention offering the most benefit per unit cost for cost-effectiveness thresholds higher than the ICER for scenario PN. The process is repeated, with the ICERs of the remaining scenarios estimated relative to the intervention identified with the lowest ICER in the previous stage of the analysis, ranked in order of increasing costs. The scenario with the lowest ICER at this stage of the analysis indicates the intervention offering the most benefit per unit cost for cost-effectiveness thresholds higher than the ICER identified as the most cost-effective in the previous stage. Presented by increasing incremental cost effectiveness ratio, the sequential analysis yields a list of recommended scenarios at increasing cost effectiveness thresholds and identifies those scenarios subject to dominance or extended dominance. A scenario is subjected to dominance when a comparator offers more benefit at lower cost, whereas a scenario is subjected to extended dominance when a comparator offers more benefit at a higher cost but lower incremental cost effectiveness ratio relative to any cost effectiveness threshold that might be selected by a decision-maker.

The current rate of radon testing in a 5 year period is 3% and rate of mitigation of existing housing above 200Bq/m^3 is 29%. The proposed incentive is a full tax credit, for the average mitigation cost of $1,800, and an increase in the radon test rate from 3% to 75% over the first 50 years of the time horizon is evaluated. It is assumed that home owners conducting a radon test are more motivated to mitigate under the tax credit incentive, so a more rapid increase from 20% to 90% over the first 20 years of the time horizon is modeled for the mitigation rate. The current test rates and mitigation rates are compared to the rates modeled under the tax credit incentive in Figure 1.

Three thresholds for mitigation of existing radon are considered, 200 Bq/m^3, 100 Bq/m^3, and 50 Bq/m^3. The Canadian radon Guideline currently recommends a mitigation threshold of 200 Bq/m^3, while adoption of the WHO reference threshold of 100 Bq/m^3 was the fourth recommendation in the review of radon policy and law in Canada by the Canadian Environmental Law Association (Dunn and Cooper 2014). The lowest threshold of 50 Bq/m^3 is included because more quality-adjusted life years can be gained and more lung cancer deaths can be prevented by reducing the smaller risks experienced by people exposed to radon levels in the middle of the distribution.

5.4.14 Uncertainty

A Monte Carlo simulation with 10,000 samples from the distributions of all uncertainty parameters: namely, parameters relating to radon exposure, age-specific health utilities, and lung cancer mortality rates and smoking prevalence by age-group and sex, was conducted to assess the uncertainty. A bootstrap analysis was then conducted, with 300 simulated datasets created using sampling with replacement from the 10,000 Monte Carlo simulations. The mean and standard error of the simulated results were estimated for the incremental costs, incremental QALYs, the ICERs and the number of lung cancer deaths prevented under each mitigation scenario, for the 2012 Canadian population, each provincial population, and those of 17 CMAs.

5.5 Results

The cost effectiveness of scenarios PN, PN T200AN, PN T100AN, and PN T50AN compared to no specific radon control measures installed at construction are listed in Table 13. The baseline scenario PN compared to no specific radon control is cost effective throughout Canada, even in the provinces/territories characterized by the lowest radon exposures. The incremental cost effectiveness ratios range from a mean (standard error) of 5,657 (10) \$/QALY for the Yukon to 53,163 (106) \$/QALY for Nunavut, with a mean of 24,809 (231) \$/QALY for Canada overall. It is estimated that 453 lung cancer deaths would be prevented if the preventive radon measures specified in the National Building Code of Canada were a Canada-wide legal requirement for new housing. Scenarios PN T200AN, PN T100AN, and PN T50AN, the testing of post-construction radon levels and activation of the preventive radon measures installed in new housing at above threshold levels, is found to be similar in cost effectiveness at all three radon thresholds compared to no specific radon control measures, with the highest threshold of 200 Bq/m^3 being the most cost effective in most of Canada. Although the activation of radon protection at above threshold radon in new housing results in easy gains in quality-adjusted life years, the radon testing and active depressurization leads to a higher cost per QALY at all three radon thresholds in all provinces/territories than just installing the mandated passive preventive measures at construction.

Table 13: Discounted ICERS for scenarios PN and PN TxxAN relative to no radon control, and lung cancer deaths for scenario PN

Region	**Scenario PN**		**Scenario PN TxxAN**		
	Discounted ICUR	**LC deaths prev.**	**T200 Discounted ICUR**	**T100 Discounted ICUR**	**T50 Discounted ICUR**
Canada	24,809 (231)	453 (2.1)	80,197 (745)	80,888 (750)	83,345 (775)
NL	37,416 (83)	4 (0)	119,751 (1,325)	121,590 (1,345)	120,937 (1,340)
NS	22,212 (49)	8 (0)	71,058 (785)	74,086 (815)	75,741 (835)
PEI	40,187 (96)	1 (0)	129,803 (1,550)	129,322 (1,545)	124,501 (1,485)
NB	18,103 (36)	7 (0)	58,769 (585)	64,773 (645)	68,952 (685)
QC	20,900 (43)	93 (0.5)	66,825 (690)	68,705 (710)	69,319 (715)
ON	34,992 (75)	120 (0.6)	112,511 (1,205)	113,992 (1,220)	112,819 (1,210)
MB	10,168 (15)	21 (0.1)	34,186 (245)	38,786 (280)	45,075 (325)
SK	12,379 (16)	25 (0.1)	40,956 (255)	44,926 (280)	51,599 (325)
AB	25,219 (36)	124 (0.4)	81,192 (570)	84,479 (595)	88,927 (625)
BC	42,927 (429)	47 (0.2)	139,906 (1,395)	139,250 (1,390)	134,838 (1,345)
NU	53,163 (106)	0.8 (0)	172,360 (1,715)	172,319 (1,715)	170,537 (1,700)
NT	13,679 (30)	0.2 (0)	44,214 (485)	45,497 (500)	46,560 (510)
YT	5,657 (10)	2 (0)	18,276 (170)	20,078 (185)	22,066 (205)

Which interventions can be determined to be cost effective under different cost effectiveness thresholds is assessed from the sequential analyses. The results of the sequential analysis for Canada are described in detail in Table 14; a sequence of interventions is identified at increasing cost effectiveness thresholds and the strategies either dominated or subject to extended dominance are listed, for all interventions and according to active radon mitigation thresholds of 200 Bq/m^3, 100 Bq/m^3, and 50 Bq/m^3. Over all interventions for Canada, the most cost effective intervention scenarios relative to the installation of passive preventive measures at construction were for an active radon mitigation threshold of 50 Bq/m^3, leading to the mitigation of the largest number of residences. The baseline preventive measures installed at construction are recommended for cost effectiveness thresholds below 50,367 $/QALY. At the active radon mitigation threshold of 50 Bq/m^3, the scenario based on current rates of radon testing and mitigation - scenario PN_T50ANRE - was the most cost effective intervention relative to the baseline PN, for cost effectiveness thresholds between 50,367 and 200,723 $/QALY. However, the incremental gain of 1,524 discounted annual incremental QALYs would require an annual investment of $76,770,646 discounted incremental dollars.

Table 14: Detailed sequential analysis of cost effectiveness thresholds for radon interventions scenarios in Canada

ALL INTERVENTIONS				
	Discounted incremental QALYs versus PN	**Discounted incremental Costs versus PN**	**Discounted incremental Cost per QALY gained versus PN**	**Sequential discounted incremental Cost per QALY Gained**
PN	0	$0	$0	$0
PN_T50ANRE	1,524	$ 76,770,646	$50,367	$50,367
PN_T50ANCRE	2,034	$ 179,178,405	$88,073	$200,723
AN_T50ANCRE	2,405	$ 418,713,350	$174,091	$646,158
Dominated strategies				
PN_T100ANRE	749	$38,896,294	$51,889	Extended dominance by PN_T50ANRE
PN_T100ANCRE	1,211	$81,363,010	$67,196	Dominated by PN_T50ANRE
PN_T200ANRE	315	$23,568,350	$74,651	Extended dominance by PN_T100ANRE
PN_T200ANCRE	513	$38,759,117	$75,477	Extended dominance by PN_T100ANRE
PN_T50AN	427	$64,504,874	$151,065	Dominated by PN_T100ANRE
PN_T100AN	181	$33,772,070	$186,586	Dominated by PN_T200ANRE
AN_T100ANCRE	1,842	$351,840,643	$190,984	Dominated by PN_T50ANCRE
AN_T200ANCRE	1,333	$321,410,572	$241,046	Dominated by PN_T50ANRE, PN_T50ANCRE
AN_T50ANRE	1,105	$315,184,035	$285,063	Dominated by PN_T100ANCRE, PN_T50ANRE, PN_T50ANCRE
PN_T200AN	76	$21,720,783	$285,800	Extended dominance by PN_T200ANRE
AN_T100ANRE	1,048	$307,816,510	$293,624	Dominated by PN_T100ANCRE, PN_T50ANRE, PN_T50ANCRE
AN_T200ANRE	996	$304,464,236	$305,531	Dominated by PN_T100ANCRE, PN_T50ANRE, PN_T50ANCRE
AN	958	$301,719,591	$314,846	Dominated by PN_T100ANCRE, PN_T50ANRE, PN_T50ANCRE

RADON MITIGATION THRESHOLD OF 200 Bq/m^3				
	Discounted incremental QALYs versus no radon control	**Discounted incremental Costs versus no radon control**	**Discounted incremental Cost per QALY gained versus no radon control**	**Sequential discounted incremental Cost per QALY Gained**
PN	0	$0	$0	$0
PN_T200ANRE	315	$23,568,350	$74,651	$74,651
PN_T200ANCRE	513	$38,759,117	$75,477	$76,794
AN_T200ANCRE	1,333	$321,410,572	$241,046	$344,749
Dominated strategies				
PN_T200AN	76	$21,720,783	$285,800	Extended dominance by PN_T200ANRE
AN_T200ANRE	996	$304,464,236	$305,531	Extended dominance by AN_T200ANCRE
AN	958	$301,719,591	$314,846	Extended dominance by AN_T200ANCRE

RADON MITIGATION THRESHOLD OF 100 Bq/m^3				
	Discounted incremental QALYs versus no radon control	**Discounted incremental Costs versus no radon control**	**Discounted incremental Cost per QALY gained versus no radon control**	**Sequential discounted incremental Cost per QALY Gained**
PN	0	$0	$0	$0
PN_T100ANRE	749	$38,896,294	$51,889	$51,889
PN_T100ANCRE	1,211	$81,363,010	$67,196	$92,072
AN_T100ANCRE	1,842	$351,840,643	$190,984	$428,362
Dominated strategies				
PN_T100AN	181	$33,772,070	$186,586	Extended dominance by PN_T100ANRE
AN_T100ANRE	1,048	$307,816,510	$293,624	Dominated by PN_T100ANCRE
AN	958	$301,719,591	$314,846	Dominated by PN_T100ANCRE

RADON MITIGATION THRESHOLD OF 50 Bq/m^3				
	Discounted incremental QALYs versus no radon control	**Discounted incremental Costs versus no radon control**	**Discounted incremental Cost per QALY gained versus no radon control**	**Sequential discounted incremental Cost per QALY Gained**
PN	0	$0	$0	$0
PN_T50ANRE	1,524	$76,770,646	$50,367	$50,367
PN_T50ANCRE	2,034	$179,178,405	$88,073	$200,723
AN_T50ANCRE	2,405	$418,713,350	$174,091	$646,158
Dominated strategies				
PN_T50AN	427	$64,504,874	$151,065	Extended dominance by PN_T50ANRE
AN_T50ANRE	1,105	$315,184,035	$285,063	Dominated by PN_T50ANRE, PN_T50ANCRE
AN	958	$301,719,591	$314,846	Dominated by PN_T50ANRE, PN_T50ANCRE

The most cost effective radon intervention scenario relative to the baseline PN scenario for Canada at an active radon mitigation threshold of 200 Bq/m^3 was PN T200ANRE, for cost effectiveness thresholds between 74,651 and 76,794 $/QALY. More benefit would be derived from the increased radon testing and mitigation rates that would result from investment in the tax credit incentive, with PN T200ANCRE being the recommended intervention (relative to PN T200ANRE) for cost effectiveness thresholds between 76,794 and 344,749 $/QALY. The combination of active depressurization in all new housing with tax credit for mitigation of existing housing above 200 Bq/m^3 is not cost effective. The same sequence of radon intervention scenarios resulted from the analysis using the active radon mitigation thresholds of 100 Bq/m^3 and 50 Bq/m^3, and the range of cost effectiveness threshold between which each scenario is optimal becomes wider as the active radon mitigation threshold is reduced. Scenario PN T100ANRE is recommended for cost effectiveness thresholds between 51,889 and 92,072 $/QALY. The curves plotted in Figure 6 show that the average cost effectiveness estimates decrease with longer time horizons, representing the higher initial investment and the delay in the resulting QALY gains. The estimates of average cost effectiveness are fairly stable for time horizons between 80 and 100 years; the curves in Figure 6 for PN T200ANRE, PN T100ANRE and PN T50ANRE flatten and change little according to year for time horizons over 80. At the highest mitigation threshold of 200 Bq/m3, the difference in cost effectiveness between the low current testing and mitigation rates and the increased rates from the tax credit incentive decreases until the curves almost merge.

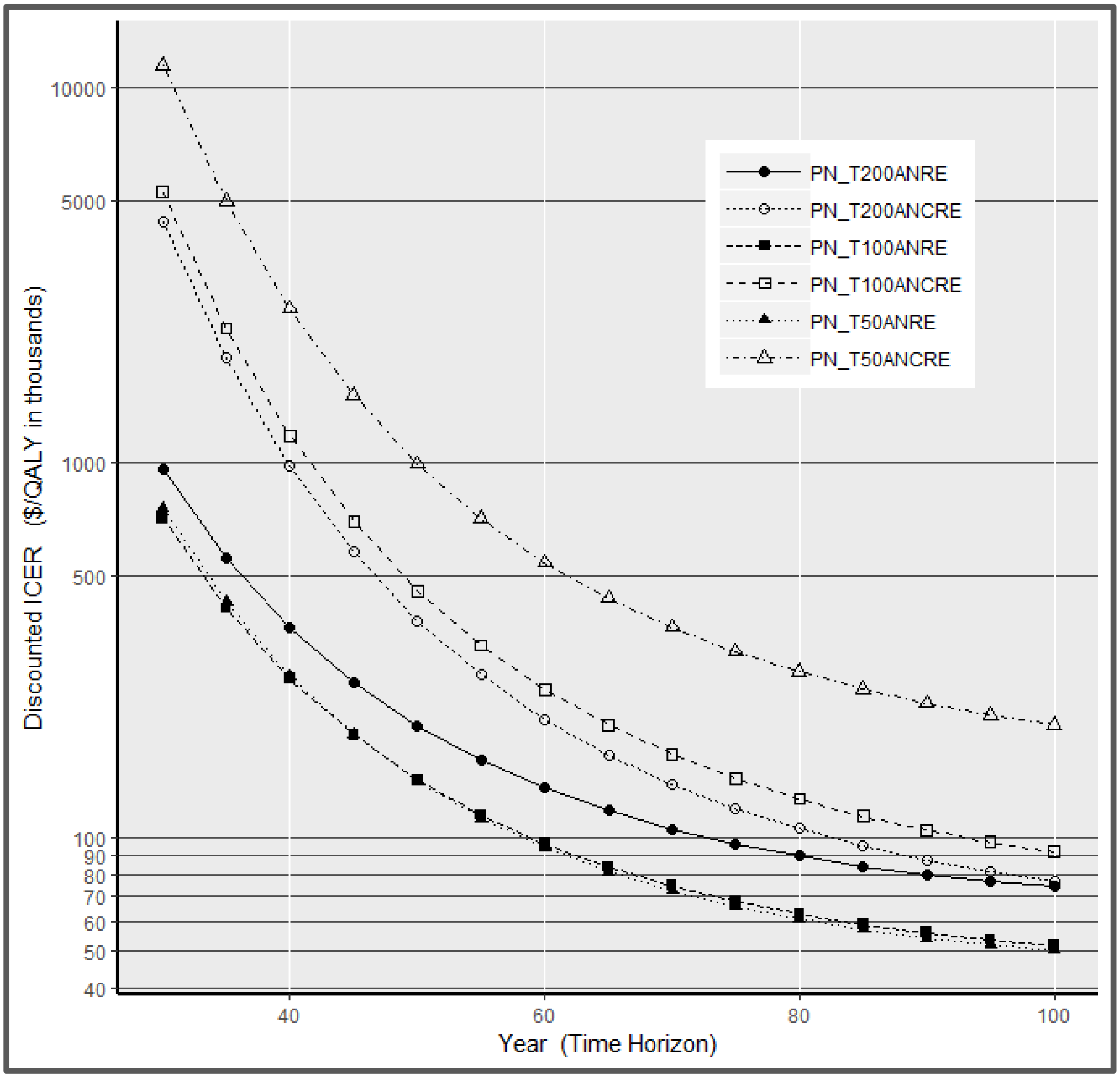

Figure 6: Cumulative ICER over time horizon for radon intervention scenarios for Canada

The results of the sequential analysis for Canada, the provinces/territories and the 17 CMAs for radon intervention scenarios more comprehensive than the baseline PN scenario relative to the baseline PN scenario are summarized in Table 15, according to active radon mitigation threshold. The provinces and CMAs can be broadly categorized into three groups based on the cost effectiveness of the radon intervention scenarios: the first group consists of populations where radon intervention scenarios are the most cost effective, the second group are those where fewer radon intervention scenarios are cost effective, and the third group are those where radon intervention scenarios are the least cost effective.

For populations where radon intervention is most cost effective, the sequential analysis indicates that the combination of the activation of preventive measures in new housing with the mitigation of existing housing at current testing and mitigation rates is recommended at all three active radon mitigation thresholds for cost effectiveness thresholds below about 50,000 \$/QALY. For this intervention scenario it is more cost effective at an active radon mitigation threshold of 100 Bq/m^3, but an active radon mitigation threshold of 200 Bq/m^3 is more cost effective in most regions for the subsequent scenario based on increased rates of testing and mitigation under the theoretical tax credit incentive. These populations include Nova Scotia, New Brunswick, Quebec, Manitoba, Saskatchewan, the Yukon, the Northwest Territories, St. John's, Halifax, St. John, Quebec City, Sherbrooke, Montreal, Ottawa-Gatineau, Kingston, Windsor, Winnipeg, Saskatoon, Regina, Calgary, and Kelowna. For the regional populations with the highest radon exposures, the activation of passive preventive measures in new housing and mitigation of existing housing with radon levels above 200 Bq/m^3 at current rates (PN T200ANRE) is recommended: for cost effectiveness thresholds between 10,338 and 32,112 \$/QALY for Winnipeg, between 32,408 and 47,051 \$/QALY for Saskatoon, and between 15,068 and 31,323 \$/QALY for the Yukon. For these three regional populations, increasing the rate of mitigation of existing housing with a tax credit (PN T200ANCRE) represents a very cost effective scenario recommended for further investment relative to PN T200ANRE. However, even for these most highly exposed populations, the most comprehensive radon intervention scenario, AN T200CRE, is only recommended for cost effectiveness thresholds over 66,754 \$/QALY for Winnipeg, over 81,178 \$/QALY for Saskatoon, and over 86,439 \$/QALY for the Yukon.

Table 15: Cost effectiveness thresholds for radon intervention scenarios based on sequential analysis of discounted ICERS for provinces/territories and census metropolitan areas

Region **CMA**	**Active radon mitigation threshold**		
	200 Bq/m^3	100 Bq/m^3	50 Bq/m^3
Canada	PN for λ < 74,651 PN T200ANRE : 74,651< λ < 76,794 PN T200ANCRE : 76,794 < λ < 344,749 AN T200CRE : λ > 344,749	PN : λ < 51,889 PN T100ANRE : 51,889 < λ < 92,072 PN T100ANCRE : 92,072 < λ < 428,362 AN T100CRE : λ > 428,362	PN : λ < 50,367 PN T50ANRE : 50,367 < λ < 200,723 PN T50ANCRE : 200,723 < λ < 646,158 AN T50CRE : λ > 646,158
NL	PN : λ < 84,859 PN T200ANRE : 84,859 < λ < 106,245 PN T200ANCRE : 106,245 < λ < 536,927 AN T200CRE : λ > 536,927	PN : λ < 62,161 PN T100ANRE : 62,161 < λ < 119.770 PN T100ANCRE : 119.770 < λ < 658,526 AN T100CRE : λ > 658,526	PN : λ < 58,444 PN T50ANRE : 58,444 < λ < 268,616 PN T50ANCRE : 268,616 < λ < 936,293 AN T50CRE : λ > 936,293
St. John's	PN : λ < 56,628 PN T200ANRE : 56,628 < λ < 71,077 PN T200ANCRE : 71,077 < λ < 200,370 AN T200CRE : λ > 200,370	PN : λ < 44,139 PN T100ANRE : 44,139 < λ < 85,683 PN T100ANCRE : 85,683 < λ < 256,467 AN T100CRE : λ > 256,467	PN : λ < 47,009 PN T50ANRE : 47,009 < λ < 171,892 PN T50ANCRE : 171,892 < λ < 459,310 AN T50CRE : λ > 459,310
NS	PN : λ < 37,982 PN T200ANRE : 37,982 < λ < 97,780 PN T200ANCRE : 97,780 < λ < 353,914 AN T200CRE : λ > 353,914	PN : λ < 34,758 PN T100ANRE : 34,758 < λ < 109,876 PN T100ANCRE : 109,876 < λ < 448,005 AN T100CRE : λ > 448,005	PN : λ < 35,998 PN T50ANRE : 35,998 < λ < 249,043 PN T50ANCRE : 249,043 < λ < 675,303 AN T50CRE : λ > 675,303
Halifax	PN : λ < 41,090 PN T200ANRE : 41,090 < λ < 59,540 PN T200ANCRE : 59,540 < λ < 175,797 AN T200CRE : λ > 175,797	PN : λ < 32,557 PN T100ANRE : 32,557 < λ < 71,235 PN T100ANCRE : 71,235 < λ < 218,534 AN T100CRE : λ > 218,534	PN : λ < 33,657 PN T50ANRE : 33,657 < λ < 143,163 PN T50ANCRE : 143,163 < λ < 365,262 AN T50CRE : λ > 365,262
PEI	PN : λ < 121,346 PN T200ANCRE : 121,346 < λ < 535,462 AN T200CRE : λ > 535,462	PN : λ < 81,869 PN T100ANRE : 81,869 < λ < 86,879 PN T100ANCRE : 86,879 < λ < 618,518 AN T100CRE : λ > 618,518	PN : λ < 62,683 PN T50ANRE : 62,683 < λ < 188,515 PN T50ANCRE : 188,515 < λ < 807,525 AN T50CRE : λ > 807,525
NB	PN : λ < 28,680 PN T200ANRE : 28,680 < λ < 113,261 PN T200ANCRE : 113,261 < λ < 322,866 AN T200CRE : λ > 322,866	PN : λ < 30,733 PN T100ANRE : 30,733 < λ < 133,530 PN T100ANCRE : 133,530 < λ < 445,726 AN T100CRE : λ > 445,726	PN : λ < 34,200 PN T50ANRE : 34,200 < λ < 321,044 PN T50ANCRE : 321,044 < λ < 755,171 AN T50CRE : λ > 755,171
St. John	PN : λ < 21,038	PN : λ < 20,896	PN : λ < 23,373

Region	Active radon mitigation threshold		
CMA	200 Bq/m^3	100 Bq/m^3	50 Bq/m^3
	PN T200ANRE : 21,038 < λ < 79,944 PN T200ANCRE : 79,944 < λ < 159,949 AN T200CRE : λ > 159,949	PN T100ANRE : 20,896 < λ < 92,545 PN T100ANCRE : 92,545 < λ < 220,065 AN T100CRE : λ > 220,065	PN T50ANRE : 23,373 < λ < 203,615 PN T50ANCRE : 203,615 < λ < 401,074 AN T50CRE : λ > 401,074
QC	PN : λ < 46,874 PN T200ANRE : 46,874 < λ < 75,836 PN T200ANCRE : 75,836 < λ < 308,861 AN T200CRE : λ > 308,861	PN : λ < 37,431 PN T100ANRE : 37,431 < λ < 81,773 PN T100ANCRE : 81,773 < λ < 392,134 AN T100CRE : λ > 392,134	PN : λ < 37,746 PN T50ANRE : 37,746 < λ < 185,295 PN T50ANCRE : 185,295 < λ < 587,962 AN T50CRE : λ > 587,962
Quebec City	PN : λ < 32,046 PN T200ANRE : 32,046 < λ < 77,924 PN T200ANCRE : 77,924 < λ < 157,570 AN T200CRE : λ > 157,570	PN : λ < 29,745 PN T100ANRE : 29,745 < λ < 88,477 PN T100ANCRE : 88,477 < λ < 214,314 AN T100CRE : λ > 214,314	PN : λ < 34,054 PN T50ANRE : 34,054 < λ < 192,250 PN T50ANCRE : 192,250 < λ < 387,438 AN T50CRE : λ > 387,438
Sherbrooke	PN : λ < 22,785 PN T200ANRE : 22,785 < λ < 75,066 PN T200ANCRE : 75,066 < λ < 123,919 AN T200CRE : λ > 123,919	PN : λ < 25,021 PN T100ANRE : 25,021 < λ < 87,327 PN T100ANCRE : 87,327 < λ < 199,167 AN T100CRE : λ > 199,167	PN : λ < 31,159 PN T50ANRE : 31,159 < λ < 300,654 PN T50ANCRE : 300,654 < λ < 379,842 AN T50CRE : λ > 379,842
Montreal	PN : λ < 26,116 PN T200ANRE : 26,116 < λ < 56,995 PN T200ANCRE : 56,995 < λ < 152,347 AN T200CRE : λ > 152,347	PN : λ < 23,638 PN T100ANRE : 23,638 < λ < 67,085 PN T100ANCRE : 67,085 < λ < 204,823 AN T100CRE : λ > 204,823	PN : λ < 25,925 PN T50ANRE : 25,925 < λ < 146,862 PN T50ANCRE : 146,862 < λ < 370,002 AN T50CRE : λ > 370,002
ON	PN : λ < 101,314 PN T200ANCRE : 101,314 < λ < 476,646 AN T200CRE : λ > 476,646	PN : λ < 71,334 PN T100ANRE : 71,334 < λ < 109,678 PN T100ANCRE : 109,678 < λ < 569,743 AN T100CRE : λ > 569,743	PN : λ < 64,251 PN T50ANRE : 64,251 < λ < 223,272 PN T50ANCRE : 223,272 < λ < 806,698 AN T50CRE : λ > 806,698
Ottawa-Gat (NCR)	PN : λ < 35,085 PN T200ANRE : 35,085 < λ < 62,709 PN T200ANCRE : 62,709 < λ < 178,129 AN T200CRE : λ > 178,129	PN : λ < 29,474 PN T100ANRE : 29,474 < λ < 67,580 PN T100ANCRE : 67,580 < λ < 237,104 AN T100CRE : λ > 237,104	PN : λ < 31,995 PN T50ANRE : 31,995 < λ < 154,302 PN T50ANCRE : 154,302 < λ < 430,712 AN T50CRE : λ > 430,712
Kingston	PN : λ < 20,316 PN T200ANRE : 20,316 < λ < 63,223 PN T200ANCRE : 63,223 < λ < 114,600 AN T200CRE : λ > 114,600	PN : λ < 20,805 PN T100ANRE : 20,805 < λ < 67,851 PN T100ANCRE : 67,851 < λ < 190,104 AN T100CRE : λ > 190,104	PN : λ < 24,089 PN T50ANRE : 24,089 < λ < 286,205 PN T50ANCRE : 286,205 < λ < 361,710 AN T50CRE : λ > 361,710
Toronto	PN : λ < 100,878	PN : λ < 60,925	PN : λ < 49,111

Region CMA	Active radon mitigation threshold		
	200 Bq/m³	100 Bq/m³	50 Bq/m³
	PN T200ANCRE : 100,878 < λ < 240,041 AN T200CRE : λ > 240,041	PN T100ANRE : 60,925 < λ < 70,066 PN T100ANCRE : 70,066 < λ < 278,325 AN T100CRE : λ > 278,325	PN T50ANRE : 49,111 < λ < 139,445 PN T50ANCRE : 139,445 < λ < 419,857 AN T50CRE : λ > 419,857
Windsor	PN : λ < 44,851 PN T200ANRE : 44,851 < λ < 104,876 PN T200ANCRE : 104,876 < λ < 243,896 AN T200CRE : λ > 243,896	PN : λ < 42,142 PN T100ANRE : 42,142 < λ < 110,800 PN T100ANCRE : 110,800 < λ < 393,936 AN T100CRE : λ > 393,936	PN : λ < 45,263 PN T50ANRE : 45,263 < λ < 498,141 PN T50ANCRE : 498,141 < λ < 739,065 AN T50CRE : λ > 739,065
MB	PN : λ < 26,920 PN T200ANRE : 26,920 < λ < 73,330 PN T200ANCRE : 73,330 < λ < 162,385 AN T200CRE : λ > 162,385	PN : λ < 27,558 PN T100ANRE : 27,558 < λ < 85,965 PN T100ANCRE : 85,965 < λ < 233,009 AN T100CRE : λ > 233,009	PN : λ < 31,815 PN T50ANRE : 31,815 < λ < 248,270 PN T50ANCRE : 248,270 < λ < 423,624 AN T50CRE : λ > 423,624
Winnipeg	PN : λ < 10,338 PN T200ANRE : 10,338 < λ < 32,112 PN T200ANCRE : 32,112 < λ < 66,754 AN T200CRE : λ > 66,754	PN : λ < 12,714 PN T100ANRE : 12,714 < λ < 51,510 PN T100ANCRE : 51,510 < λ < 99,705 AN T100CRE : λ > 99,705	PN : λ < 13,872 PN T50ANRE : 13,872 < λ < 337,436 PN T50ANCRE : 337,436 < λ < 195,583 AN T50CRE : λ > 195,583
SK	PN : λ < 40,962 PN T200ANRE : 40,962 < λ < 82,125 PN T200ANCRE : 82,125 < λ < 181,178 AN T200CRE : λ > 181,178	PN : λ < 36,569 PN T100ANRE : 36,569 < λ < 88,200 PN T100ANCRE : 88,200 < λ < 250,329 AN T100CRE : λ > 250,329	PN : λ < 43,222 PN T50ANRE : 43,222 < λ < 226,809 PN T50ANCRE : 226,809 < λ < 451,839 AN T50CRE : λ > 451,839
Saskatoon	PN : λ < 32,408 PN T200ANRE : 32,408 < λ < 47,051 PN T200ANCRE : 47,051 < λ < 81,473 AN T200CRE : λ > 81,473	PN : λ < 25,627 PN T100ANRE : 25,627 < λ < 51,435 PN T100ANCRE : 51,435 < λ < 141,052 AN T100CRE : λ > 141,052	PN : λ < 41,454 PN T50ANRE : 41,454< λ < 294,042 AN T50CRE : λ > 294,042
Regina	PN : λ < 29,540 PN T200ANRE : 29,540 < λ < 70,343 PN T200ANCRE : 70,343 < λ < 157,652 AN T200CRE : λ > 157,652	PN : λ < 43,580 PN T100ANRE : 43,580 < λ < 152,963 PN T100ANCRE : 152,963 < λ < 221,925 AN T100CRE : λ > 221,925	PN : λ < 48,976 PN T50ANRE : 48,976 < λ < 726,413 AN T50CRE : λ > 726,413
AB	PN : λ < 117,923 PN T200ANCRE : 117,923 < λ < 319,082 AN T200CRE : λ > 319,082	PN : λ < 82,362 PN T100ANRE : 82,362 < λ < 122,819 PN T100ANCRE : 122,819 < λ < 394,867 AN T100CRE : λ > 394,867	PN : λ < 84,388 PN T50ANRE : 84,388 < λ < 243,257 PN T50ANCRE : 243,257 < λ < 694,940 AN T50CRE : λ > 694,940
Edmonton	PN : λ < 69,939	PN : λ < 46,161	PN : λ < 67,017

Region CMA	Active radon mitigation threshold		
	200 Bq/m³	100 Bq/m³	50 Bq/m³
	PN T200ANRE : 69,939 < λ < 75,629 PN T200ANCRE : 75,629 < λ < 167,605 AN T200CRE : λ > 167,605	PN T100ANRE : 46,161 < λ < 77,395 PN T100ANCRE : 77,395 < λ < 244,175 AN T100CRE : λ > 244,175	PN T50ANRE : 67,017 < λ < 224,539 PN T50ANCRE : 224,539 < λ < 455,488 AN T50CRE : λ > 455,488
Calgary	PN : λ < 61,524 PN T200ANRE : 61,524 < λ < 76,924 PN T200ANCRE : 76,924 < λ < 160,122 AN T200CRE : λ > 160,122	PN : λ < 43,976 PN T100ANRE : 43,976 < λ < 78,667 PN T100ANCRE : 78,667 < λ < 246,522 AN T100CRE : λ > 246,522	PN : λ < 66,563 PN T50ANRE : 66,563 < λ < 279,135 PN T50ANCRE : 279,135 < λ < 457,605 AN T50CRE : λ > 457,605
BC	PN : λ < 237,160 PN T200ANCRE : 237,160 < λ < 537,050 AN T200CRE : λ > 537,050	PN : λ < 113,786 PN T100ANCRE : 113,786 < λ < 600,976 AN T100CRE : λ > 600,976	PN : λ < 86,670 PN T50ANRE : 86,670 < λ < 186,790 PN T50ANCRE : 186,790 < λ < 744,417 AN T50CRE : λ > 744,417
Kelowna	PN : λ < 38,576 PN T200ANRE : 38,576 < λ < 60,563 PN T200ANCRE : 60,563 < λ < 136,326 AN T200CRE : λ > 136,326	PN : λ < 31,232 PN T100ANRE : 31,232 < λ < 63,450 PN T100ANCRE : 63,450 < λ < 202,446 AN T100CRE : λ > 202,446	PN : λ < 41,570 PN T50ANRE : 41,570 < λ < 179,574 PN T50ANCRE : 179,574 < λ < 387,946 AN T50CRE : λ > 387,946
Vancouver	PN : λ < 350,807 PN T200ANCRE : 350,807 < λ < 529,883 AN T200CRE : λ > 529,883	PN : λ < 155,387 PN T100ANCRE : 155,387 < λ < 580,563 AN T100CRE : λ > 580,563	PN : λ < 112,403 PN T50ANRE : 112,403 < λ < 186,062 PN T50ANCRE : 186,062 < λ < 687,702 AN T50CRE : λ > 687,702
NU	PN: λ < 614,873 S2: 614,873 < λ < 1,099,488 AN T200CRE: λ > 1,099,488	PN: λ < 607,554 AN T100CRE: λ > 607,554	PN: λ < 367,270 PN T50ANCRE : 367,270 < λ < 611,050 AN T50CRE : λ > 611,050
NT	PN : λ < 22,598 PN T200ANRE : 22,598 < λ < 54,379 PN T200ANCRE : 54,379 < λ < 210,315 AN T200CRE : λ > 210,315	PN : λ < 19,382 PN T100ANRE : 19,382 < λ < 59,204 PN T100ANCRE : 59,204 < λ < 259,396 AN T100CRE : λ > 259,396	PN : λ < 19,317 PN T50ANRE : 19,317 < λ < 131,165 PN T50ANCRE : 131,165 < λ < 382,718 AN T50CRE : λ > 382,718
YT	PN : λ < 15,068 PN T200ANRE : 15,068 < λ < 31,323 PN T200ANCRE : 31,323 < λ < 86,439 AN T200CRE : λ > 86,439	PN : λ < 15,801 PN T100ANRE : 15,801 < λ < 36,547 PN T100ANCRE : 36,547 < λ < 118,710 AN T100CRE : λ > 118,710	PN : λ < 18,679 PN T50ANRE : 18,679 < λ < 89,542 PN T50ANCRE : 89,542 < λ < 211,350 AN T50CRE : λ > 211,350

The sequential analysis indicates that fewer radon intervention scenarios are cost effective for the following populations: Newfoundland, PEI, Ontario, Alberta, Toronto, and Edmonton. The activation of passive preventive measures in new housing and mitigation of existing housing with radon levels above 100 Bq/m^3 and 50 Bq/m^3 at current rates are recommended for cost effectiveness thresholds around 50,000 $/QALY for Newfoundland, Toronto and Edmonton. The cost effectiveness threshold for Newfoundland at which the activation of passive preventive measures in new housing and the mitigation of existing housing at current rates becomes recommended is 62,161 $/QALY for an active radon mitigation threshold of 100 Bq/m^3, and 58,444 $/QALY for an active radon mitigation threshold of 50 Bq/m^3. For Edmonton, this radon intervention scenario becomes recommended at a cost effectiveness threshold of 46,161 $/QALY for an active radon mitigation threshold of 100 Bq/m^3, of 67,017 $/QALY for an active radon mitigation threshold of 50 Bq/m^3. The cost effectiveness threshold for active radon mitigation thresholds of 100 Bq/m^3 and 50 Bq/m^3 for activation of passive preventive measures in new housing and mitigation of existing housing at current rates is a bit higher in Alberta, about 80,000 $/QALY. For the populations of PEI and Ontario, only the activation of passive preventive measures in new housing and mitigation of existing housing with radon levels above 50 Bq/m^3 at current rates relative to baseline PN is recommended for cost effectiveness thresholds below about 60,000 $/QALY.

The radon intervention scenarios are the least cost effective for the populations exposed to the lowest residential radon levels, including British Columbia, Nunavut and Vancouver. The combination of the activation of passive preventive measures in new housing with the mitigation of existing houses in British Columbia becomes recommended at a cost effectiveness threshold of 86,670 $/QALY for an active radon mitigation threshold of 50 Bq/m^3.

The annual number of lung cancer deaths prevented for radon intervention scenarios identified in the sequential analysis for all three active radon mitigation thresholds for Canada, the provinces/territories and CMAs are listed in Table 16. More lung cancer deaths are prevented annually as the active mitigation threshold is reduced for each scenario: for Canada, PN T200ANRE, PN T100 ANRE, and PN T50 ANRE would prevent a mean (SE) of 54 (3), 160 (5), and

386 (7) radon attributed lung cancer deaths respectively. A similar pattern in preventable lung cancer deaths results at each active radon mitigation threshold for the increased radon test and mitigation rates under the tax credit incentive and for the combination of an active stack in new housing with mitigation of above threshold existing housing: for Canada, PN T200ANRE, PN T200 ANCRE, and AN T20CRE would prevent a mean (SE) of 54 (3), 100 (4), and 429 (4) annual radon attributed lung cancer deaths respectively. The number of lung cancer deaths prevented annually are low for the provinces and CMAs with smaller populations.

The average annual number of mitigations of existing housing for radon intervention scenarios identified in the sequential analysis for all three active radon mitigation thresholds for Canada, the provinces/territories and CMAs are listed in Table 17. The average annual number of mitigations depends on the radon exposure and the size of the population. The largest average number of homes are mitigated at the lowest threshold for each scenario. For Canada, the mean (SE) of the average annual number of mitigations of existing housing at mitigation thresholds of 200 Bq/m^3, 100 Bq/m^3 and 50 Bq/m^3 is 862 (38), 2,412 (57), and 5,821 (87) respectively, at the current mitigation rate, and the mean (SE) is 12,456 (550), 34,839 (827), and 84,074 (1,254) respectively, with the tax credit incentive. In Winnipeg, the population for which the radon intervention is estimated to be the most cost effective, the mean (SE) of the average annual number of mitigations of existing housing at a mitigation threshold of 200 Bq/m^3, 100 Bq/m^3 and 50 Bq/m^3 is 140 (1), 242 (2), and 278 (2) respectively, at the current mitigation rate, and the mean (SE) is 2,017 (20), 3,491 (27), and 3,998 (30) respectively, with the tax credit incentive. A much greater average annual number of existing homes are mitigated under the tax credit incentive, which results in a shorter time until remediation of most above threshold exposures in the housing stock, ranging from 40 to 55 years. For the national analysis, remediation of most above threshold exposure in the housing stock would require 150 years at the current rates of testing and mitigation of existing housing. This analysis is based on a time horizon of 100 years, and, therefore, periods over 100 years are specified as such in Tables 17 and 18.

Table 16: Annual number of preventable radon attributable lung cancer deaths for radon intervention scenarios

Region	Scenario	Number of preventable lung cancer deaths [mean (SE)] at radon threshold		
		200 Bq/m^3	100 Bq/m^3	50 Bq/m^3
Canada	PN TxxANRE	54 (3)	160 (5)	386 (7)
	PN TxxANCRE	100 (4)	274 (6)	570 (7)
	AN TxxCRE	429 (4)	561 (6)	770 (7)
NL	PN TxxANRE	1 (0)	2 (0.1)	4 (0.1)
	PN TxxANCRE	1 (0.1)	3 (0.1)	6 (0.1)
	AN TxxCRE	4 (0.1)	6 (0.1)	8 (0.1)
St. John's, NL	PN TxxANRE	1 (0)	2 (0)	5 (0.1)
	PN TxxANCRE	1 (0)	3 (0.1)	7 (0.1)
	AN TxxCRE	7 (0)	8 (0.1)	10 (0.1)
NS	PN TxxANRE	2 (0.1)	5 (0.1)	11 (0.2)
	PN TxxANCRE	4 (0.1)	9 (0.2)	15 (0.2)
	AN TxxCRE	9 (0.1)	13 (0.2)	19 (0.2)
Halifax, NS	PN TxxANRE	1 (0)	4 (0.1)	9 (0.1)
	PN TxxANCRE	2 (0.1)	6 (0.1)	13 (0.1)
	AN TxxCRE	9 (0.1)	11 (0.1)	16 (0.1)
PEI	PN TxxANRE	NA	0 (0)	1 (0)
	PN TxxANCRE	0 (0)	0 (0)	1 (0)
	AN TxxCRE	1 (0)	1 (0)	1 (0)
NB	PN TxxANRE	4 (0.1)	8 (0.1)	14 (0.2)
	PN TxxANCRE	6 (0.1)	12 (0.2)	19 (0.2)
	AN TxxCRE	11 (0.1)	16 (0.2)	21 (0.2)
St. John, NB	PN TxxANRE	1 (0)	1 (0)	3 (0)
	PN TxxANCRE	1 (0)	2 (0)	4 (0)
	AN TxxCRE	2 (0)	3 (0)	4 (0)
QC	PN TxxANRE	16 (0.8)	40 (1.2)	91 (1.7)
	PN TxxANCRE	27 (1.1)	69 (1.6)	131 (1.8)
	AN TxxCRE	94 (1.1)	127 (1.5)	172 (1.7)
Quebec City, QC	PN TxxANRE	4 (0.1)	9 (0.2)	18 (0.2)
	PN TxxANCRE	5 (0.1)	12 (0.2)	23 (0.2)
	AN TxxCRE	19 (0.1)	24 (0.2)	29 (0.2)
Sherbrooke, QC	PN TxxANRE	2 (0)	5 (0.1)	8 (0.1)
	PN TxxANCRE	3 (0.1)	7 (0.1)	10 (0.1)
	AN TxxCRE	7 (0)	9 (0.1)	11 (0)
Montreal, QC	PN TxxANRE	15 (0.6)	41 (0.9)	89 (1.1)
	PN TxxANCRE	27 (0.8)	67 (1.1)	126 (1.1)
	AN TxxCRE	75 (0.7)	106 (1.0)	147 (1.0)
ON	PN TxxANRE	NA	34 (1.2)	84 (1.8)
	PN TxxANCRE	22 (1.0)	58 (1.6)	127 (2.1)

Region	Scenario	Number of preventable lung cancer deaths [mean (SE)] at radon threshold		
		200 Bq/m^3	100 Bq/m^3	50 Bq/m^3
	AN TxxCRE	109 (1.1)	136 (1.6)	185 (2.0)
Ottawa-Gat, ON	PN TxxANRE	5 (0.2)	14 (0.3)	36 (0.4)
	PN TxxANCRE	9 (0.3)	27 (0.4)	53 (0.4)
	AN TxxCRE	27 (0.2)	42 (0.4)	60 (0.3)
Kingston, ON	PN TxxANRE	1 (0)	3 (0)	7 (0)
	PN TxxANCRE	2 (0)	6 (0)	8 (0)
	AN TxxCRE	4 (0)	7 (0)	8 (0)
Toronto, ON	PN TxxANRE	NA	18 (0.6)	56 (1.1)
	PN TxxANCRE	8 (0.5)	28 (0.9)	84 (1.3)
	AN TxxCRE	96 (0.6)	108 (0.9)	141 (1.1)
Windsor, ON	PN TxxANRE	1 (0)	3 (0)	8 (0.1)
	PN TxxANCRE	2 (0)	7 (0.1)	10 (0)
	AN TxxCRE	4 (0)	9 (0.1)	10 (0)
MB	PN TxxANRE	7 (0.2)	18 (0.3)	37 (0.3)
	PN TxxANCRE	12 (0.3)	30 (0.3)	47 (0.3)
	AN TxxCRE	27 (0.2)	41 (0.3)	51 (0.2)
Winnipeg, MB	PN TxxANRE	21 (0.3)	52 (0.4)	80 (0.4)
	PN TxxANCRE	40 (0.4)	72 (0.4)	NA
	AN TxxCRE	58 (0.4)	81 (0.3)	87 (0.2)
SK	PN TxxANRE	5 (0.1)	13 (0.2)	30 (0.3)
	PN TxxANCRE	8 (0.2)	22 (0.3)	39 (0.2)
	AN TxxCRE	25 (0.2)	35 (0.2)	45 (0.2)
Saskatoon, SK	PN TxxANRE	4 (0.1)	14 (0.1)	27 (0.1)
	PN TxxANCRE	5 (0.1)	19 (0.1)	NA
	AN TxxCRE	25 (0.1)	30 (0.1)	31 (0.1)
Regina, SK	PN TxxANRE	7 (0.1)	14 (0.1)	17 (0.1)
	PN TxxANCRE	9 (0.1)	15 (0.1)	NA
	AN TxxCRE	16 (0.1)	18 (0)	18 (0)
AB	PN TxxANRE	NA	30 (0.6)	78 (0.9)
	PN TxxANCRE	13 (0.5)	41 (0.8)	102 (0.9)
	AN TxxCRE	106 (0.5)	119 (0.7)	145 (0.7)
Edmonton, AB	PN TxxANRE	9 (0.3)	33 (0.5)	76 (0.6)
	PN TxxANCRE	12 (0.3)	45 (0.5)	86 (0.5)
	AN TxxCRE	83 (0.3)	96 (0.4)	107 (0.4)
Calgary, AB	PN TxxANRE	10 (0.3)	35 (0.4)	76 (0.5)
	PN TxxANCRE	13 (0.3)	48 (0.5)	84 (0.5)
	AN TxxCRE	75 (0.3)	90 (0.4)	99 (0.3)
BC	PN TxxANRE	NA	NA	15 (0.5)
	PN TxxANCRE	2 (0.2)	9 (0.4)	23 (0.6)
	AN TxxCRE	37 (0.3)	42 (0.4)	51 (0.6)

Region	Scenario	Number of preventable lung cancer deaths [mean (SE)] at radon threshold		
		200 Bq/m^3	100 Bq/m^3	50 Bq/m^3
Kelowna, BC	PN TxxANRE	1 (0)	4 (0.1)	9 (0.1)
	PN TxxANCRE	2 (0)	6 (0.1)	11 (0.1)
	AN TxxCRE	8 (0)	11 (0.1)	13 (0.1)
Vancouver, BC	PN TxxANRE	1 (0.1)	2 (0.1)	6 (0.2)
	PN TxxANCRE	1 (0.1)	3 (0.2)	8 (0.3)
	AN TxxCRE	26 (0.2)	27 (0.2)	30 (0.3)
NU	PN TxxANRE	NA	NA	NA
	PN TxxANCRE	AN: 1 (0)	NA	NA
	AN TxxCRE	1 (0)	1 (0)	1 (0)
NT	PN TxxANRE	0 (0)	0 (0)	0 (0)
	PN TxxANCRE	0 (0)	0 (0)	1 (0)
	AN TxxCRE	0 (0)	0 (0)	1 (0)
YT	PN TxxANRE	0 (0)	1 (0)	2 (0)
	PN TxxANCRE	1 (0)	1 (0)	2 (0)
	AN TxxCRE	2 (0)	2 (0)	3 (0)

Table 17: Annual number of mitigations of existing housing for radon intervention scenarios

Region	Mitigation Rate	Period until most above threshold radon mitigated	Number of mitigations of existing housing at active radon mitigation threshold mean (SE)		
			200 Bq/m^3	100 Bq/m^3	50 Bq/m^3
Canada	current	>100 y	862 (38)	2,412 (57)	5,821 (87)
	tax credit	45 y	12,456 (550)	34,839 (827)	84,074 (1,254)
NL	current	>100 y	13 (1)	36 (1)	82 (1)
	tax credit	50 y	171 (8)	461 (12)	1,039 (18)
St. John's	current	90 y	6 (0)	16 (0)	39 (1)
	tax credit	40 y	113 (4)	307 (6)	771 (9)
NS	current	>100 y	38 (1)	88 (2)	175 (3)
	tax credit	45 y	555 (17)	1,280 (27)	2,539 (38)
Halifax	current	>100 y	12 (0)	34 (1)	84 (1)
	tax credit	45 y	190 (6)	517 (10)	1,299 (15)
PEI	current	>100 y	NA	4 (0)	11 (0)
	tax credit	45 y	21 (1)	65 (2)	166 (4)

Region	Mitigation Rate	Period until most above threshold radon mitigated	Number of mitigations of existing housing at active radon mitigation threshold mean (SE)		
			200 Bq/m^3	100 Bq/m^3	50 Bq/m^3
NB	current	>100 y	64 (2)	128 (2)	216 (3)
	tax credit	50 y	811 (19)	1,629 (26)	2,752 (33)
St. John	current	>100 y	6 (0)	14 (0)	28 (0)
	tax credit	40 y	106 (3)	249 (4)	493 (5)
QC	current	>100 y	208 (8)	550 (13)	1,189 (18)
	tax credit	45 y	3,026 (118)	8,002 (188)	17,284 (266)
Quebec City	current	90 y	29 (1)	69 (1)	141 (2)
	tax credit	40 y	526 (15)	1,255 (22)	2,564 (30)
Sherbrooke	current	95 y	16 (0)	36 (0)	52 (1)
	tax credit	40 y	303 (5)	671 (7)	958 (9)
Montreal	current	>100 y	159 (5)	403 (7)	844 (9)
	tax credit	45 y	2,390 (68)	6,078 (105)	12,715 (138)
ON	current	>100 y	214 (10)	584 (16)	1,501 (26)
	tax credit	45 y	3,083 (144)	8,409 (229)	21,602 (369)
Ottawa-Gat	current	>100 y	60 (2)	188 (3)	406 (4)
	tax credit	50 y	756 (20)	2,360 (35)	5,109 (48)
Kingston	current	>100 y	12 (0)	37 (0)	51 (1)
	tax credit	45 y	188 (4)	551 (6)	771 (7)
Toronto	current	>100 y	40 (2)	141 (4)	530 (7)
	tax credit	40 y	742 (44)	2,641 (76)	9,890 (126)
Windsor	current	>100 y	28 (1)	102 (1)	143 (1)
	tax credit	55 y	322 (7)	1,155 (11)	1,628 (13)
MB	current	>100 y	88 (2)	223 (3)	360 (4)
	tax credit	45 y	1,310 (28)	3,327 (42)	5,374 (53)
Winnipeg	current	>100 y	140 (1)	242 (2)	278 (2)
	tax credit	45 y	2,017 (20)	3,491 (27)	3,998 (30)
SK	current	>100 y	52 (1)	156 (2)	292 (3)
	tax credit	45 y	817 (20)	2,453 (32)	4,590 (44)
Saskatoon	current	75 y	16 (0)	60 (1)	77 (1)
	tax credit	40 y	261 (5)	1,005 (5)	1,287 (11)
Regina	current	>100 y	43 (0)	62 (1)	69 (1)
	tax credit	45 y	714 (6)	1,025 (8)	1,134 (9)
AB	current	90 y	83 (3)	261 (5)	750 (7)
	tax credit	40 y	1,503 (53)	4,745 (95)	13,627 (136)
Edmonton	current	80 y	43 (1)	177 (2)	323 (3)
	tax credit	40 y	735 (21)	3,017 (39)	5,488 (48)
Calgary	current	85 y	50 (1)	199 (2)	316 (3)

Region	Mitigation Rate	Period until most above threshold radon mitigated	Number of mitigations of existing housing at active radon mitigation threshold mean (SE)		
			200 Bq/m³	100 Bq/m³	50 Bq/m³
	tax credit	40 y	874 (22)	3,490 (39)	5,543 (47)
BC	current tax credit	>100 y 45 y	NA 324 (28)	NA 1,232 (54)	245 (6) 3,709 (90)
Kelowna	current tax credit	>100 y 40 y	8 (0) 157 (4)	29 (0) 543 (7)	52 (1) 967 (8)
Vancouver	current tax credit	80 y 40 y	6 (1) 99 (10)	20 (1) 342 (19)	62 (2) 1,056 (32)
NU	current tax credit	95 y 45 y	NA 0 (0)	NA 0 (0)	NA 1 (0)
NT	current tax credit	>100 y 50 y	1 (0) 15 (1)	3 (0) 38 (1)	7 (0) 85 (1)
YT	current tax credit	>100 y 45 y	3 (0) 43 (1)	6 (0) 95 (1)	11 (0) 163 (2)

Table 18:Annual discounted cost of mitigations of existing housing for radon intervention scenarios

Region	Mitigation Rate	Period until most above threshold radon mitigated	Cost of mitigation of existing housing ($1000) at active radon mitigation threshold mean (SE)		
			200 Bq/m³	100 Bq/m³	50 Bq/m³
Canada	current tax credit	>100 y 45 y	903 (40) 16,813 (742)	2,525 (60) 47,025 (1,116)	6,094 (91) 113,480 (1,692)
NL	current tax credit	>100 y 50 y	14 (1) 229 (11)	37 (1) 619 (16)	84 (1) 1,396 (24)
St. John's	current tax credit	90 y 40 y	8 (0) 156 (5)	19 (0) 423 (8)	47 (1) 1,062 (12)
NS	current tax credit	>100 y 45 y	40 (1) 752 (24)	93 (2) 1,734 (37)	185 (3) 3,439 (51)

Halifax	current	>100 y	14 (0)	37 (1)	93 (1)
	tax credit	45 y	260 (8)	707 (14)	1,775 (20)
PEI	current	>100 y	NA	5 (0)	12 (0)
	tax credit	45 y	29 (2)	88 (3)	225 (5)
NB	current	>100 y	66 (2)	132 (2)	223 (3)
	tax credit	50 y	1,091 (25)	2,192 (35)	3,704 (44)
St. John	current	>100 y	7 (0)	16 (0)	32 (0)
	tax credit	40 y	146 (4)	344 (6)	681 (7)
QC	current	>100 y	220 (9)	581 (14)	1,254 (19)
	tax credit	45 y	4,094 (160)	10,826 (254)	23,382 (360)
Quebec City	current	90 y	36 (1)	85 (1)	174 (2)
	tax credit	40 y	730 (20)	1,742 (30)	3,559 (41)
Sherbrooke	current	95 y	20 (0)	44 (0)	62 (1)
	tax credit	40 y	419 (7)	927 (10)	1,323 (12)
Montreal	current	>100 y	173 (5)	439 (8)	919 (10)
	tax credit	45 y	3,259 (93)	8,289 (143)	17,338 (188)
ON	current	>100 y	224 (10)	610 (17)	1,566 (27)
	tax credit	45 y	4,158 (194)	11,343 (309)	29,137 (498)
Ottawa-Gat	current	>100 y	61 (2)	190 (3)	411 (4)
	tax credit	50 y	1,010 (26)	3,152 (46)	6,824 (64)
Kingston	current	>100 y	14 (0)	40 (0)	56 (1)
	tax credit	45 y	257 (5)	753 (8)	1,055 (10)
Toronto	current	>100 y	46 (2)	164 (4)	613 (7)
	tax credit	40 y	1,018 (44)	3,623 (76)	13,570 (126)
Windsor	current	>100 y	28 (1)	102 (1)	143 (1)
	tax credit	55 y	428 (9)	1,536 (15)	2,165 (18)
MB	current	>100 y	95 (2)	241 (3)	389 (4)
	tax credit	45 y	1,782 (38)	4,526 (57)	7,311 (72)
Winnipeg	current	>100 y	147 (1)	254 (2)	290 (2)
	tax credit	45 y	2,723 (28)	4,713 (37)	5,398 (41)
SK	current	>100 y	58 (1)	175 (2)	327 (3)
	tax credit	45 y	1,118 (27)	3,360 (44)	6,287 (61)
Saskatoon	current	75 y	20 (0)	78 (1)	100 (1)
	tax credit	40 y	365 (7)	1,401 (12)	1,794 (15)
Regina	current	>100 y	50 (0)	71 (1)	79 (1)
	tax credit	45 y	975 (8)	1,400 (11)	1,548 (12)
AB	current	90 y	100 (4)	316 (6)	907 (9)
	tax credit	40 y	2,067 (74)	6,527 (130)	18,746 (187)
Edmonton	current	80 y	54 (2)	221 (3)	401 (4)
	tax credit	40 y	1,014 (29)	4,160 (53)	7,565 (66)
Calgary	current	85 y	61 (2)	243 (3)	386 (3)
	tax credit	40 y	1,202 (31)	4,801 (54)	7,625 (65)
BC	current	>100 y	NA	NA	266 (6)

	tax credit	45 y	441 (38)	1,674 (73)	5,040 (122)
Kelowna	current tax credit	>100 y 40 y	10 (0) 216 (5)	34 (0) 743 (9)	60 (1) 1,325 (12)
Vancouver	current tax credit	80 y 40 y	7 (1) 138 (14)	25 (1) 475 (26)	79 (2) 1,464 (44)
NU	current tax credit	95 y 45 y	NA 36 (0)	NA 305 (62)	NA 1,469 (151)
NT	current tax credit	>100 y 50 y	1 (0) 20 (1)	3 (0) 51 (1)	7 (0) 114 (2)
YT	current tax credit	>100 y 45 y	3 (0) 59 (1)	7 (0) 129 (2)	12 (0) 221 (2)

The discounted average cost (in thousands of dollars) of annual mitigation of existing housing for radon intervention scenarios identified in the sequential analysis for all three active radon mitigation thresholds for Canada, the provinces/territories and CMAs are listed in Table 18. Only the cost of mitigation of existing housing is considered, for which a tax credit would apply, and depends on the number of mitigations listed in Table 17. In Canada, the mean (SE) of the discounted cost of annual mitigations of existing housing at a mitigation threshold of 200 Bq/m^3, 100 Bq/m^3 and 50 Bq/m^3 is 0.9 (0.040), 2.5 (0.060), and 6.1 (0.091) million dollars, respectively, at the current mitigation rate, and the mean (SE) is 17 (0.7), 47 (1.1), and 113 (1.7) million dollars, respectively, with the tax credit incentive. In Winnipeg, the population for which the radon intervention is estimated to be the most cost effective, the mean (SE) of the discounted cost of annual mitigations of existing housing at a mitigation threshold of 200 Bq/m^3, 100 Bq/m^3 and 50 Bq/m^3 is 147 (1), 265 (2), and 290 (2) thousand dollars, respectively, at the current mitigation rate, and the mean (SE) is 2.7 (0.03), 4.7 (0.04), and 5.4 (0.04) million dollars, respectively, with the tax credit incentive.

5.6 Discussion

The most cost effective radon intervention in all target populations in Canada is the installation of passive preventive measures at construction. It is straightforward to mandate preventive measures installed at construction in the building code and it is the least costly as well as the most cost effective radon reduction intervention. The requirement of the rough-in for an active depressurization system also allows for much easier reduction of the highest radon exposures experienced by the target population because mitigation of above threshold radon in new housing is much less costly than retrofitting existing housing.

This analysis models the implementation over time of practical radon intervention scenarios to represent the gradual turnover of the housing stock to include radon control measures, through both radon prevention in new housing and mitigation of existing housing. The sequential analysis identifies the optimal radon intervention scenarios in all target populations in Canada according to increasing cost effectiveness threshold relative to the baseline scenario: the activation of the passive preventive measures installed in housing at construction and the mitigation of above threshold radon in existing housing – at the current rate and then at an increased rate modelled using a theoretical tax credit incentive, while the active depressurization in all new housing and mitigation of above threshold radon in existing housing is generally found not to be cost effective. The most cost effective intervention scenario relative to the baseline PN is the activation of the passive preventive measures installed in new housing and the mitigation of above threshold radon in existing housing at the current rate. It is recommended for Canada for cost effectiveness thresholds between 74,651 and 76,794 \$/QALY for an active radon mitigation threshold of 200 Bq/m^3, for cost effectiveness thresholds between 51,889 and 92,072 \$/QALY for an active radon mitigation threshold of 100 Bq/m^3, and for cost effectiveness thresholds between 50,367 and 200,723 \$/QALY for an active radon mitigation threshold of 50 Bq/m^3. The mean annual number of radon attributable lung cancer deaths prevented at the three mitigation thresholds are 54, 160, and 386 respectively. A sequence of cost effective radon intervention scenarios for regional populations in Canada is described, with a greater degree and/or rate of radon reduction achieved from scenarios that include a lower active radon mitigation threshold and/or a tax credit incentive for mitigation of existing housing.

The activation of the passive preventive measures installed in new housing and the mitigation of above threshold radon in existing housing is cost effective at the current rate for many regional populations in Canada at all three radon mitigation thresholds considered, recommended for cost effectiveness thresholds lower than 50,000 $/QALY. The activation of passive preventive measures in new housing and active mitigation of existing housing at radon above the active mitigation threshold is only cost effective for populations with lower radon exposures at the lower active radon mitigation thresholds assessed, at 100 Bq/m^3 and 50 Bq/m^3. Other regional populations, such as CMAs not included in this analysis, might also be classified in this group if assessed. The region with higher radon potential within BC (zone 2) has not been evaluated separately in this analysis, although Kelowna is a CMA located in this region that is evaluated. The most comprehensive scenario for radon reduction, for active depressurization in all new housing and in existing housing above the active radon mitigation threshold, is generally not cost effective. The sequential analysis of residential radon intervention scenarios show that it is cost effective for many populations in Canada to combine preventive radon measures in new housing with mitigation of above threshold radon in existing housing.

Increasing the degree and/or rate of reduction in radon exposure would require significantly more investment due to the much higher average annual number and cost of mitigations of existing housing that result from reducing the active radon mitigation threshold and from offering a tax credit incentive. In Canada, the mean annual number of mitigations of existing housing is 862 at the current rate and a radon threshold of 200 Bq/m^3, which would increase to 2,412 if the radon threshold were reduced to 100 Bq/m^3, and to 5,821 at a radon threshold of 50 Bq/m^3. The mean annual number of mitigations would increase with the tax credit incentive to 12,456 at a radon threshold of 200 Bq/m^3, would total 34,839 at a radon threshold of 100 Bq/m^3 with the tax credit incentive, and 84,074 at a radon threshold of 50 Bq/m^3. The corresponding annual mean discounted cost of mitigation of existing housing is 0.9 million dollars at the current rate and a radon threshold of 200 Bq/m^3, which would increase to 2.5 million dollars if the radon threshold were reduced to 100 Bq/m^3, and to 6.0 million dollars at a radon threshold of 50 Bq/m^3. The mean annual discounted cost of mitigation of existing housing would increase with the tax incentive to 16,813 at a radon threshold of 200 Bq/m^3, to 47,025 if the radon threshold were reduced to 100 Bq/m^3, and to 113,480 at a radon threshold of 50 Bq/m^3. The period until mitigation of all above radon threshold housing in the population is achieved would almost be halved using the increased rate of testing and mitigation for existing housing, reduced from 150 years to 45 years in Canada overall, and for a population with higher growth rate and housing stock growth such as Edmonton, that period would be reduced from 80 years to 40 years.

The degree of reduction in radon is increased at lower thresholds for active radon mitigation and is also affected by the underlying radon distribution. In a population with high radon exposures characterized by a median (geometric mean) radon exposure close to the highest radon threshold for active mitigation of 200 Bq/m^3, such as Winnipeg, the intervention scenarios become less cost effective as the active radon mitigation threshold is decreased because a smaller number of dwellings at lower radon exposures are mitigated with each decrease. For a population with intermediate radon exposures, such as Ontario, the intervention scenario that combines activation of preventive radon measures in new housing with mitigation of above threshold radon in existing housing becomes progressively more cost effective as the active radon mitigation threshold is decreased from 200 Bq/m^3 to 100 Bq/m^3, and to 50 Bq/m^3, due to the increase in the number of dwellings with each decrease in the radon threshold despite lower individual radon reductions per dwelling mitigated.

Similar conclusions were drawn from comparison of radon intervention scenarios in European studies. The results of five health economic evaluations conducted in European countries to estimate the cost per quality-adjusted life year gained for radon interventions scenarios are listed in Table 19: in Sweden (Svensson et al. 2018), Ireland (Pollard & Fenton 2014), the UK (Gray et al. 2009), Germany (Haucke 2010) and Norway (Stigum et al. 2003). For most regional populations in Canada, passive radon prevention measures installed in new construction relative to no radon control and screening and mitigation scenarios relative to passive preventive measures were found to be cost effective. While screening and mitigation scenarios for existing housing were not found to be cost effective in Ireland or the UK, installing a radon membrane and sealing joints and cracks was determined to be cost effective in new housing (Pollard & Fenton 2014; Gray et al. 2009). Intervention scenarios that include screening and mitigation of existing housing were identified by sequential analysis at cost effectiveness thresholds generally considered reasonable at all three radon mitigation thresholds for many regional populations exposed to higher residential radon in Canada. Screening and mitigation of existing housing has been identified as the most cost-effective intervention in high radon areas in two studies in the UK (Coskeran et al. 2009; Gray et al. 2009). In the UK, Germany, and Norway, screening and mitigation scenarios are more cost-effective at lower action levels because more houses will be remediated (and if the intervention is mandatory) when the lower action levels is still higher than the geometric mean of the radon distribution, yielding greater benefit for the same screening cost (Gray et al. 2009; Haucke 2010; Stigum et al. 2003). In Sweden, screening and mitigation of new and existing housing at an action level of 200 Bq/m^3 is currently recommended, and it was determined in a recent analysis that it was cost effective to reduce the action level from 200 to 100 Bq/m^3 for screening and mitigation of new housing but not for existing housing (Svensson et al. 2018).

Norway and Canada have similar residential radon exposures, and the ICER estimates for the scenario described by passive radon prevention in new houses and screening and mitigation in existing housing are cost effective (compared to no radon control): 23,000 USD/QALY for a radon mitigation threshold of 200 Bq/m^3 discounted at 3% for Norway in 2003, and at 34,424 $/QALY and 38,307 $/QALY discounted at 1.5% in Canada, for current rates at radon mitigation thresholds of 100 Bq/m^3 and 50 Bq/m^3 respectively. Sweden also has similar residential radon exposures, and currently mandates the remediation of radon levels above 200 Bq/m^3 in new housing and recommends it for existing housing. The incremental cost effectiveness ratio of reducing the active radon mitigation threshold in Sweden to 100 Bq/m^3 was estimated using a discount rate of 3% and a time horizon of 25 years: for new housing the ICER was 39,000 (25,000) €/QALY – including (excluding) costs of life-years gained, and for existing housing the ICER was 130,000 (90,000) €/QALY – including (excluding) costs of life-years gained (Svensson et al. 2018). In Canada, the incremental cost effectiveness ratios of reducing the active radon mitigation threshold from 200 to 100 Bq/m^3 for intervention scenarios that combine that combine the gradual implementation throughout the housing stock of the activation of new housing and mitigation of existing housing are estimated. Excluding costs for life-years gained, these ICER estimates are 35,327 $/QALY at the current rates (PN T100ANRE relative to

Table 19: Cost effectiveness of radon interventions in European countries

Country (reference)	Radon Arithmetic Mean (Bq/m^3)	Discount Rate	ICERs
Sweden (Svensson et al. 2018)	90	3%	**New housing** (reducing action level from 200 to 100 Bq/m^3) 39,000 (25,000) €/QALY – including (excluding) costs of life-years gained **Existing housing** (reducing action level from 200 to 100 Bq/m^3) 130,000 (90,000) €/QALY – including (excluding) costs of life-years gained
Ireland (Pollard & Fenton, 2014)	89	4%	**New housing** 12,524 €/QALY (Radon membrane) 81,866 €/QALY (Active stack) **Remediation of existing housing (for action level of 200 Bq/m^3)** 33,395 €/QALY (Testing funded by government) 26,672 €/QALY (Testing & remediation of social housing) 32,866 €/QALY (Requirement for radon level upon sale)
Germany (Haucke 2010)	49	3% costs 1.5% effects	**Universal screening and mandatory mitigation of existing housing** 25,181 $€_{2008}$/QALY (for action level of 100 Bq/m^3) 38,269 $€_{2008}$/QALY (for action level of 200 Bq/m^3) 75,040 $€_{2008}$/QALY (for action level of 400 Bq/m^3)
UK (Gray et al., 2009)	21	3.5% costs 1.5% effects	**New housing** 11,400 £/QALY (Radon membrane)
Norway (Stigum et al., 2003)	75	3%	**New housing and remediation of existing housing above 200 Bq/m^3** 23,000 USD/QALY

PN T200ANRE) and 61,098 $/QALY at the increased rate under the tax credit incentive (PN T100ANCRE relative to PN T200ANCRE). The estimates for Sweden and Canada are roughly comparable despite differences in the analyses because the benefits of reduced lung cancer mortality occur years to decades after the costs of remediation are incurred, and the lower discount rate, longer time horizon and gradual implementation used in the analysis for Canada result in lower ICER estimates.

Significant increases in radon testing and mitigation by homeowners were reported from radon control incentives used in Iowa, US (Bain et al. 2016). An increase of 20% in number of radon tests in 2014 compared to 2009 after free radon test kits were made available, and an increase of 108%, from 2,600 to 5,400, were completed after grants to homeowners in low income communities and offers of low-interest bank loans for mitigation were offered. In the province of Manitoba, the Manitoba Hydro utility has recently instituted a lower interest loan that allows the homeowner to add the cost of an active depressurization system to the monthly hydro bill and pay it back over a period of about 5 years. It will be interesting to evaluate any increase in the rate of radon testing and mitigation that might result from the incentive offered by this initiative. The significant increases in the number of energy efficiency retrofits conducted by homeowners in Canada from 2008-2012 and the radon testing and mitigation reported in Iowa were both reported following the introduction of a tax credit that covered the bulk of the construction costs. The tax credit modelled in this analysis would cover the estimated mean retrofit mitigation cost of $1,800 per home owner. The Green Budget Recommendations 2016 (Green Budget Coalition 2015) proposed a tax credit up to $3000 for radon mitigation. It is not expected that the 15% tax credit proposed in the Green Budget Recommendations 2018 (Green Budget Coalition 2017) would provide the same incentive for homeowners to mitigate. Incentives have led to widespread adoption of new policies when compared to mandatory measures that can be interpreted as punitive, with a successful example in Canada being the home energy retrofit tax credit. The success of tax credit incentives in energy efficiency policies have been credited to framing a policy to make the "best" choice more appealing to consumers, sometimes referred to as a nudge (Thaler and Sunstein 2003). Loss aversion is a behavioural anomaly that results from reference dependence, and in the setting of radon mitigation can be explained as worry about potential future loss and uncertainty about future benefits. The framing of choices is important to help consumers making complex decisions, reducing non-standard decision making, and a tax credit can present an investment by a homeowner as a bargain instead of a potential loss (Gillingham and Palmer 2013). The next step in Canada could be to investigate the response to a tax credit incentive modeled in this analysis by running a pilot project in a city with high radon such as Regina or Winnipeg.

The projected increases in radon testing and mitigation rates for housing over the 100 years modelled would require crafting an effective radon awareness campaign to accompany the radon preventive measures in new housing and tax credits incentives for mitigation of existing housing. It has been reported in both BC, Canada, and in Finland that radon testing rates were higher in radon prone areas where radon prevention measures are mandated in new construction (Cheng 2016; Valmari et al. 2014). However, a review of risk communication strategies used in BC emphasized that all housing needs to be tested to control radon risk in a population, that it is important to raise radon awareness in areas that have not been designated as radon-prone areas instead of targeting radon-prone areas (Cheng et al. 2016). The establishment of a mandatory radon registry would enable collection of radon exposure and mitigation data for Canadian housing, as recommended by Dunn et al. (2014) and Miller (2012). A mandatory or voluntary radon registry could in time convince homeowners to test, as opposed to the current situation wherein homeowners refrain from testing for radon because it is not required but must be revealed if known at point of sale.

Health care falls under provincial jurisdiction in Canada, and the cost effectiveness of interventions to reduce radon can be compared to lung cancer screening and treatment programs in Canada. A lung cancer screening program targeted at smokers in Canada estimated an incremental cost effectiveness ratio of 52,000 $/QALY (compared to no screening), based on a 20 year time horizon and a discount rate of 3% (Goffin et al. 2015). Based on a 6 year time horizon and discount rates ranging from 3% to 5%, two health economic evaluations were recently conducted for a lung cancer screening program targeted at people identified as being at high risk of lung cancer in Canada and in Ontario, reporting ICER estimates ranging from 20,724 to 32,352 $/QALY and an ICER estimate of 32,476 $/QALY, respectively (Cressman et al. 2017; Thao 2014). The most cost effective radon intervention scenario relative to the baseline PN scenario for many provincial populations in Canada was the activation of passive preventive measures in new housing and mitigation of above threshold in existing housing, becoming recommended at a cost effectiveness threshold of 51,889 (50,367) $/QALY at a mitigation threshold of 100 (50) Bq/m^3. For Manitoba, this radon intervention is cost effective at all three radon mitigation thresholds: at cost effectiveness thresholds between

26,920 and 73,330 \$/QALY at an active radon mitigation threshold of 200 Bq/m^3, between 27,558 and 85,965 \$/QALY at an active radon mitigation threshold of 100 Bq/m^3, and between 31,819 and 248,270 \$/QALY at an active radon mitigation threshold of 50 Bq/m^3. For Ontario, this scenario is more cost effective at the two lower radon mitigation thresholds: for cost effectiveness thresholds between 71,334 and 109,678 \$/QALY at an active radon mitigation threshold of 100 Bq/m^3, and between 64,251 and 223,272 \$/QALY at an active radon mitigation threshold of 50 Bq/m^3. The cost effectiveness of prevention of radon attributed lung cancer by screening and mitigation of residential radon compares favourably with screening programs targeting people identified as being at high risk of lung cancer currently being assessed in Canada. Treatment of lung cancer using expensive new genotype-specific drugs was also investigated by Thao (2014), and the ICER was estimated to be 32,913 \$/QALY for Gefitinib as firstline treatment in EGFR+ patients and 111,851 \$/QALY for Gefitinib and Crizotinib treatment in EGFR+ and ALK+ patients. Screening people at high risk of lung cancer enables earlier treatment and prevention of lung cancer results in gains in quality-adjusted life expectancy and reductions in lung cancer treatment costs. Some investment in lung cancer prevention by means of residential radon remediation and lung cancer screening could be considered worthwhile over an extended time horizon in a population with a public health system that includes treatment programs for lung cancer.

The most important limitation in this analysis stems from estimating the cost of mitigating existing housing due to the variation in housing characteristics and the long time horizon modelled. A lower-end estimate of the construction cost was used in this analysis, which is expected to be conservative because the cost of mitigation has been dropping steadily as mitigation becomes more common and contractors more experienced. Ongoing research at the National Research Council of Canada is helping to reduce the uncertainty in estimating the efficiency of radon interventions in Canada. The evaluation of the residential radon exposures is another important limitation of this analysis. Although a representative national radon survey using 3 month-long measurement using alpha-track detectors was conducted, measurement error remains significant. A correction was made for measurement error when estimating the “true” radon exposures used in this analysis, from an estimate of the year-to-year variation determined from comparing the two national radon surveys completed recently. Minimal error was expected to result from use of the simplified housing model because the ten-year averages (2007-2016) for housing stock growth and new house starts included 5 years when new household formation exceeded new construction (2012-2016) and 5 years when the reverse was true (2007–2011). However, the estimates of the housing stock are an important limitation because they are collected in the voluntary national housing survey (NHS), which is known to be subject to bias from under-reporting (Reynaud 2015).

The range and effectiveness of the preventive radon measures modeled in this analysis were limited by the data currently available to the mean effectiveness for two housing interventions, passive preventive measures installed at construction and a full active soil depressurization system. As ongoing research into the pre- and post-mitigation radon levels for houses in Canada becomes available, new data could be used to fit a probability distribution describing the range in effectiveness of an active soil depressurization system that could then be added to the analysis. In addition, tests are being conducted to measure the reduction in residential radon achieved from full passive stacks in BC and in Ottawa, which is expected to be effective for housing with radon levels between 150 and 400 Bq/m^3, and the option of a full passive stack could also be added to a future analysis.

The ICERs for the radon intervention scenarios estimated in this analysis are quite conservative because they are limited to lung cancer mortality. An improved understanding of the benefits of residential radon remediation would result from extending the health economic evaluations to include the reductions in quality of life due to radon attributed lung cancer morbidity and the lung cancer treatment costs saved when lung cancer cases are prevented. Health utility drops according to non-small-cell lung cancer status from 1 for no lung cancer, to 0.88 for stage 1, to 0.80 for stages 2 and 3, and to 0.69 for stage 4 (Thao 2014). Lung cancer treatment costs are high and growing, due to the recent inclusion of very expensive new chemotherapy drugs that are tailored to specific genetic mutations, such as gefitinib for EGFR mutations and crizotinib for ALK mutations. The annual cost of lung cancer treatment was estimated to be $17 million dollars in the Green Budget Recommendations 2016 (Green Budget Coalition 2015).

The cost effectiveness of interventions to reduce radon in the UK included the quality of life gains and costs saved through the prevention of radon attributed lung cancer morbidity (Gray et al. 2009). Cost effectiveness estimates at the provincial level would be required in Canada because treatment costs vary by province since healthcare is under provincial jurisdiction. Ongoing radon surveys would also help to reduce the uncertainty in population radon exposures and to evaluate the success of radon control measures enacted in Canada.

5.7 Conclusions

A sequence of interventions is recommended at increasing cost effectiveness thresholds in the Canadian context, allowing flexibility under budget constraints. It is very cost effective to install radon preventive measures in new construction compared to no radon control in all regions across Canada, and it is recommended that this be mandated in the few provinces that have yet to adopt this part of the National Building Code of Canada. It is recommended that voluntary radon mitigation of existing housing be promoted through public education and a tax credit incentive. The most cost effective radon intervention scenario for Canada (compared to the baseline passive preventive measures in new housing) is the combination of the activation of preventive measures in new housing with the mitigation of existing housing at current testing and mitigation rates. This radon intervention scenario is recommended at cost effectiveness thresholds between 51,889 and 92,072 $/QALY at an active radon mitigation threshold of 100 Bq/m^3. For most regional populations, this intervention scenario is more cost effective at an active radon mitigation threshold of 100 Bq/m^3, but an active radon mitigation threshold of 200 Bq/m^3 is more cost effective for the subsequent intervention scenario described by increased rates of testing and mitigation under the theoretical tax credit incentive. It is important to emphasize that greater investment in radon reduction is recommended where a range of intervention scenarios are cost effective, either for a lower radon mitigation threshold or using a tax credit incentive. These regional populations include Nova Scotia, New Brunswick, Quebec, Manitoba, Saskatchewan, the Yukon, the Northwest Territories, St. John's, Halifax, St. John, Quebec City, Sherbrooke, Montreal, Ottawa-Gatineau, Kingston, Windsor, Winnipeg, Saskatoon, Regina, Calgary, and Kelowna. A public health investment in radon remediation in new and existing housing could decrease the time to achieve widespread reduction of the highest radon exposures in the housing stock. Residential radon interventions should be implemented in Canada to reduce exposures to this very modifiable cause of lung cancer and help reduce the increasing lung cancer burden in an ageing Canadian population.

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Chapter 6 – Cost-utility analysis of practical interventions to reduce residential radon in existing housing in Canada

6.1 Abstract

Background: Interventions to reduce residential radon can be divided into two main types, the installation of prevention measures during construction in new housing and the screening and mitigation of existing housing.

Objectives: To estimate the cost effectiveness of radon interventions for screening and mitigation of existing housing for the 2012 population in Canada and to assess the structural uncertainty associated with the choice of model used in the cost-utility analysis.

Methods: The incremental cost utility ratios of radon interventions for screening and mitigation of existing housing are estimated using both a Markov cohort model and a discrete event simulation model that is based on the assessment of the radon exposure of individual households. A societal perspective, a lifetime horizon and a discount rate of 1.5% are adopted.

Results: The results for the discrete event simulation are comparable to those from the Markov cohort model for mitigation of existing housing; it appears that minimal structural uncertainty is associated with the choice of model used for this cost-utility analysis. At a radon mitigation threshold of 200 (100) Bq/m^3, the discounted ICERs for current rates of screening and mitigation of existing housing compared to no specific radon measures in Canada are 62,451 (58,866) $/QALY using a Markov cohort model and 74,648 (59,556) $/QALY using discrete event simulation. The cost effectiveness is improved by increasing the rate of screening and mitigation, and at these higher rates there is little difference in cost effectiveness between using a mitigation threshold of 100 and 200 Bq/m^3. The screening and mitigation interventions for existing housing are characterized by low costs but they are subject to extended dominance or are dominated by passive preventive measures installed in new housing at construction.

Conclusions: The mitigation of radon in existing housing in Canada is estimated to be fairly cost-effective, the cost-effectiveness would improve at increased rates of radon testing and mitigation. The estimates of incremental cost effectiveness ratios do not appear to be sensitive to the choice of model used in the cost-utility analysis.

6.2 Background

Recent research addressing residential radon is transitioning from refining quantification of the radon associated burden of lung cancer to the assessment of regional health economic evaluations of interventions to reduce residential radon and the associated lung cancer burden. Interventions to reduce residential radon can be divided into two main types, the installation of prevention measures during construction and the mitigation of existing housing. Preventive measures installed at construction may be activated if radon testing is conducted upon completion of the construction and radon exposure if above the mitigation threshold. The mitigation of existing housing is generally more expensive because installing a sub-slab depressurization system is much more expensive after construction is completed and significant screening costs are required to identify the housing that is above the mitigation threshold.

Several European countries have evaluated the cost effectiveness of radon preventive measures installed at construction and the screening and mitigation of existing housing above specific radon mitigation thresholds. Preventing radon entry into new houses, by installing a radon-impermeable membrane and sealing joints and sumps under the floor, was the intervention determined in several national analyses to have a lower cost per QALY than the screening and mitigation of houses with radon above a specific action level (Gray et al. 2009; Pollard and Fenton 2014; Svensson et al. 2018). While only the prevention of radon is cost-effective at lower mean indoor radon levels, screening and remediation has been identified as the most cost-effective intervention in high radon areas (Coskeran et al. 2009; Gray et al. 2009). At the higher mean radon exposure in Ireland, screening and mitigation was determined to be most cost effective at a mitigation threshold of 200 Bq/m^3 (Pollard and Fenton 2014). At lower mean indoor radon exposures, screening and mitigation is more cost-effective at lower action levels and at higher mitigation rates (Gray et al. 2009; Haucke 2010; Stigum et al. 2003). In more highly radon exposed populations in the UK, the cost effectiveness for radon prevention in new housing and for the screening and mitigation of existing housing was determined to depend upon several factors including the percentage of housing above the mitigation threshold and the mitigation rate (Coskeran et al. 2006a, 2006b).

Cohort models are a common form of decision-analytic model in health economic evaluation. A Markov cohort model simulates disease progression in a population by characterizing health into mutually exclusive health states, with changes in health over time modelled as a Markov chain using transition probabilities between health states over the cycle length. A microsimulation model can be used to follow the progression of each individual in a population. Since residential radon is the exposure of interest it is the household that is modelled, with all residents exposed to the sampled household radon. A discrete event simulation model allows the history of an individual to be incorporated into the progression along the time horizon, calculating the length of time an individual is in each state. By contrast, the assumption in a Markov model is that the transition probabilities, of moving from one state to another, do not depend on the past of the individual or the time spent in a given state. The main disadvantages of using microsimulation models are the much larger amount of input data required and the increase in computer power/time needed to generate stable results.

Two approaches were used to estimate the mean residential radon exposure for the population of Switzerland: a weighted national average residential radon exposure based on aggregating measurement at the municipal level from a representative randomized survey, and a microsimulation approach based on estimating the residential radon exposure of each resident in each household in the population from a multivariable log-linear regression model (Hauri et al. 2013). The more complex microsimulation model was found to yield very comparable results and can be applied in the future to studying specific regions or subgroups in the population. The economic model for a lung cancer screening program based on a 20 year time horizon in Canada employed a microsimulation model that allowing screening to be investigated for age-specific cohorts, from which it was determined that screening a 50-year old group was the most cost effective (Goffin et al. 2015).

In Canada, while radon control in new housing is addressed in the National Building Code (NBC), these provisions are advisory and some provinces have yet to adopt the NBC recommendations regarding radon control measures. The population-weighted percentage of Canadians in 2012 living in homes with radon concentrations above the Radon Guidelines' threshold of 200 Bq/m^3

was estimated to be 6.9% (Health Canada 2012). The five provinces with the highest percentage of residents exposed to above threshold radon are New Brunswick at 20.6%, the Yukon at 19.6%, Manitoba at 19.4%, Saskatchewan at 15.7%, and Nova Scotia at 10.7%. The Radon Guideline recommends that radon levels above 200 Bq/m^3 be mitigated, but the homeowners are responsible for all the costs and compliance is voluntary. A health economic evaluation is conducted to estimate the incremental cost effectiveness ratio (ICER) for the mitigation of existing housing in Canada using two models, a Markov cohort model and a discrete event simulation model.

6.3 Research Question

The objective of this analysis is to estimate the incremental cost utility ratios (ICERs) for radon interventions to reduce residential radon exposures in existing housing for the 2012 population in Canada. The structural uncertainty associated with the choice of model used in the cost-utility analysis is assessed by using both a Markov cohort model and a discrete event simulation model to evaluate the ICERs for screening and mitigation of existing housing. The cost effectiveness of screening and mitigation of existing housing is compared to other radon intervention scenarios using a sequential analysis. Determining which interventions are cost effective can help policy-makers to balance investment in lung cancer prevention with lung cancer treatment.

6.4 Methods

6.4.1 Target populations

Analysis was conducted for the 2012 Canadian population modelled with replacement over the 100 year period of the analysis (Statistics Canada 2012b). The population growth was modelled using census data averaged from 2006-2016.

6.4.2 Intervention strategies

The screening and mitigation of existing housing is evaluated using two rates of screening and mitigation, the current rate and an increased rate under a theoretical tax credit incentive, and for three radon mitigation thresholds, at 200, 100, and 50 Bq/m^3. Under the theoretical tax credit incentive, the screening rate was assumed to rise quickly, and mitigation rates were assumed to increase quickly for home owners who choose to test for radon exposure. Figure 7 demonstrates the increase in radon testing and mitigation rates over the 100 year time horizon, for both the current situation and under a tax credit incentive.

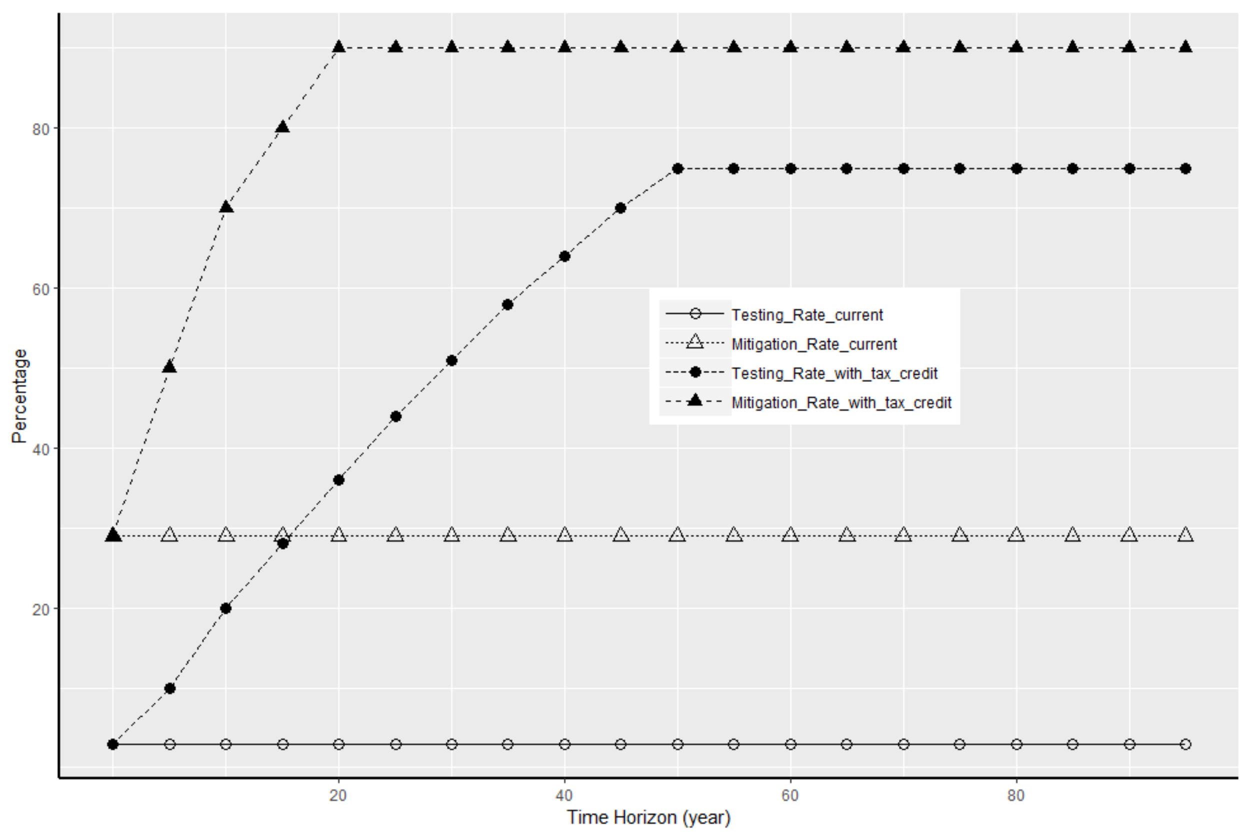

Figure 7: Radon testing and mitigation rates at current levels and with a tax credit incentive

(same information as Figure 4 in Chapter 3)

The interventions for screening and mitigation of existing housing are compared to other possible radon interventions. Passive preventive measures installed in new construction are evaluated, with retesting of radon levels in subsequently mitigated housing every 5 years and in below threshold housing every 10 years. The installation of preventive measure in new housing is also evaluated in combination with testing and mitigation of existing housing at current rates and under a tax credit incentive. The intervention scenarios described below are summarized in Table 20.

Radon Intervention Scenarios

Scenario PN – Baseline option requiring the passive preventive measures described in the 2010 National Building Code of Canada to be installed in all new housing.

Scenarios PN T200AN, PN T100AN, PN T50AN – Passive preventive measures installed in all new housing, and for above threshold radon (T200, T100, T50) an active depressurization system installed in new housing.

Scenarios PN T200ANRE, PN T100ANRE, PN T50ANRE –Passive preventive measures in new housing and, at above threshold radon levels, active depressurization system in new housing and retrofit of existing housing at current mitigation rate.

Scenarios PN T200ANCRE, PN T100ANCRE, PN T50ANCRE – Passive preventive measures in new housing and, at above threshold radon levels, active depressurization system in new housing and retrofit of existing housing at increased mitigation rate under tax credit incentive

Scenarios T200RE, T100RE, T50RE – retrofit active depressurization system in existing housing above the radon mitigation threshold at current mitigation rate

Scenarios T200CRE, T100CRE, T50CRE – retrofit active depressurization system in existing housing above the radon mitigation threshold at increased mitigation rate under tax credit incentive

6.4.3 Study perspective and time horizon

A societal perspective was adopted because the costs associated with adapting housing to reduce residential radon exposure occur outside the health care system. A time horizon of one hundred years was selected to represent the lifelong benefits for reducing residential radon exposure experienced by all current and future residents of the remediated housing.

Table 20: Radon intervention scenarios compared to no specific radon control

Scenario (PN, AN, RE) Threshold (T)	New Construction		Existing Housing		Notes
	Rn test	Radon prevention	Rn test	Retrofit	
PN	×	Passive	×	×	**P**assive preventive measures in **N**ew construction only
PN T200AN	✓	Passive/Active	×	×	**P**assive preventive measures in **N**ew construction, At Rn>200 Bq/m3: **A**ctivated depressurization in **N**ew construction
PN T100AN	✓	Passive/Active	×	×	**P**assive preventive measures in **N**ew construction, At Rn>100 Bq/m3: **A**ctivated depressurization in **N**ew construction
PN T50AN	✓	Passive/Active	×	×	**P**assive preventive measures in **N**ew construction, At Rn>50 Bq/m3: **A**ctivated depressurization in **N**ew construction
PN T200ANRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>200 Bq/m3: **A**ctivated depressurization in **N**ew construction & **R**etrofit for activated depressurization of **E**xisting housing
PN T100ANRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>100 Bq/m3: **A**ctivated depressurization in **N**ew construction & **R**etrofit for activated depressurization of **E**xisting housing
PN T50ANRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>50 Bq/m3: **A**ctivated depressurization in **N**ew construction & **R**etrofit for activated depressurization of **E**xisting housing
PN T200ANCRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>200 Bq/m3: **A**ctivated depressurization in **N**ew construction & **C**redit for **R**etrofit for activated depressurization of **E**xisting housing
PN T100ANCRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>100 Bq/m3: **A**ctivated depressurization in **N**ew construction & **C**redit for **R**etrofit for activated depressurization of **E**xisting housing
PN T50ANCRE	✓	Passive/Active	✓	✓	**P**assive preventive measures in **N**ew construction At Rn>50 Bq/m3: **A**ctivated depressurization in **N**ew construction & **C**redit for **R**etrofit for activated depressurization of **E**xisting housing
T200RE	×	×	✓	✓	At Rn>200 Bq/m3: **R**etrofit for activated depressurization of **E**xisting housing
T100RE	×	×	✓	✓	At Rn>100 Bq/m3:

Scenario (PN, AN, RE) Threshold (T)	New Construction		Existing Housing		Notes
	Rn test	Radon prevention	Rn test	Retrofit	
					Retrofit for activated depressurization of **E**xisting housing
T50RE	×	×	✓	✓	At Rn>50 Bq/m3: **R**etrofit for activated depressurization of **E**xisting housing
T200CRE	×	×	✓	✓	At Rn>200 Bq/m3: **C**redit for **R**etrofit for activated depressurization of **E**xisting housing
T100CRE	×	×	✓	✓	At Rn>100 Bq/m3: **C**redit for **R**etrofit for activated depressurization of **E**xisting housing
T50CRE	×	×	✓	✓	At Rn>50 Bq/m3: **C**redit for **R**etrofit for activated depressurization of **E**xisting housing

6.4.4 Discounting

The discount rate used for the base analysis is 1.5%, recommended by the Canadian Agency for Drugs and Technologies in Health (CADTH 2017). A discount rate of 0% is also used for comparison purposes.

6.4.5 Modelling

The proportion of existing housing in the housing stock gradually reduces because new housing is built and some older housing is replaced. A household is assumed to have a constant radon exposure randomly selected from the lognormal residential radon distribution, until screening and mitigation occurs to reduce it. The passive preventive measures installed during the construction of new housing halve the sampled radon exposure, and are further reduced should a full depressurization system be activated following screening. The 2011 values and growth rates averaged from 2007-2017 data were used to model housing stock growth, new construction incorporating preventive radon measures, and radon testing and subsequent mitigation of a proportion of the existing housing over five year periods.

An abridged period life-table approach was also based on 5 year age intervals. The age distribution of the 2012 population was based on the census and the age-and sex-specific all cause mortality and lung incidence were derived from Statistics Canada databases. A hazard rate was calculated from the reported probability of death and used to calculate the probability of surviving to the end of each 5 year interval. For each time interval, the probability of dying is one minus the probability of survival. A radon exposed person's mortality risk is modelled as the sum of the baseline risk and the risk due to radon exposure. This analysis is based on lifetime radon exposure, assessing the excess relative risk of lung cancer mortality from radon for each age-group in the population, and incorporating the timing and the reductions in radon exposures from the interventions described in the housing model. The probability of surviving to the beginning of each age interval, of dying during the age interval, the intensity ratio between all cause and lung cancer mortality, and the population growth over the time horizon are used to estimate the baseline and radon exposed life expectancy (LE, LE_E) and lifetime risk (LR, LR_E) of lung cancer. The population attributable risk used to determine the number of lung cancer death attributable to radon is calculated in equation 1 from the population-averaged lifetime risk in the exposed population (LR_E) and the baseline lifetime risk for a theoretical unexposed population (LR) as described in Brand et al. (2005):

$$PAR = \frac{LR_E - LR}{LR_E} \qquad (Eq\ 1)$$

In the discrete event simulation, a two parameter Weibull distribution is fitted to the survival times determined from the abridged period life-table analysis. The survival time is predicted for male smokers, male nonsmokers, female smokers and female nonsmokers, incorporating the reduction in radon from mitigation of housing that may occur at any time during the lifetime of the person. The number of residents per household is predicted using the cumulative distribution for the data for Canada, which average 2.5 residents per household. A second household is modelled if the predicted lifetime of the housing unit is longer than the predicted lifetime of all the residents in the first household. The lifetime of the housing unit is modelled using a normal distribution, based on the reduction in existing housing over the time horizon in the housing model. The time to mitigation is predicted using the cumulative probability generated from the number of housing units mitigated in each 5 year interval in the housing model, at both testing and mitigation rates assessed.

6.4.6 Residential radon distribution

The representative national radon distribution was found to follow a lognormal distribution with geometric mean of 41.7 Bq/m^3 and a geometric standard deviation of 2.64. The distribution was determined by applying the fitdistplus function in R using population weights and the maximum likelihood estimator to the measurements from the representative national radon survey conducted in Canada between 2009-2011 (Health Canada 2012). Residential radon data below the detection limit of 15 Bq/m^3 were approximated in this analysis by half that value, 7.5 Bq/m^3. An adjustment was made for year-to-year variation, estimated from the difference for the 33 census metropolitan areas (CMA) between the 2009-2011 national survey and the 2012-2013 CMA survey.

6.4.7 Housing Model

A model based on the 2011 CMHC data was used to represent changes to the housing stock in Canada over the 100 year time horizon. The model was restricted to dwellings occupied by usual residents, and ten years of data (2007 to 2016) was averaged to model the growth rate of the housing stock and the number of new housing units constructed over 5 year periods . The rate of new construction is higher than the growth of the housing stock, as some of the existing housing is replace over time.

6.4.8 All Cause and Lung Cancer Mortality by Smoking Status

All-cause probability of death for 2012 was reported for Canada in the Death Database (Statistics Canada 2012a) by sex- and age-specific category. Lung cancer incidence rates were adjusted assuming that lung cancer mortality constitutes the same proportion of lung cancer incidence rates (Statistics Canada 2012c) as were reported in the National Cancer Institute SEER cancer statistics review for the US population between 1975 and 2009 (Howlader et al. 2012), based on similar patterns of high mortality rates and low life expectancy post diagnosis in both countries. Smoking status was reported according to current daily smoker and nonsmoker for 2012 by sex- and age-specific category (Table 21) in the Canadian Community Health Survey (CCHS) (Statistics Canada 2012b). This analysis used the values reported by the American Cancer Society Cancer Prevention Study II (ACS CPS-II) for relative risk of all cause and lung cancer mortality for smokers versus nonsmokers (RR_e) by sex and age category (Thun et al. 1997). The relative risk for smokers versus nonsmokers by sex- and age-specific category (Table 21) were used to adjust all-cause and lung cancer mortality rates for smoking (Villeneuve and Mao 1994). Based on recent research estimating the relative risk of former smokers (Kenfield et al. 2008; Pesch et al. 2012), former smokers in the population were modelled according to time since quitting, using a linear decrease in relative risk (from lifetime smoker to lifetime nonsmoker) over a 20 year period. Smokers who quit more than 20 years prior were assumed to be equivalent to lifelong nonsmokers.

Table 21: Age-specific HUI, and age- and sex-specific relative risk of all-cause and lung cancer mortality

Age-Group (years)	**HUI Mean (sd)**	**RR all-cause mortality M**	**RR all-cause mortality F**	**RR lung cancer mortality M**	**RR lung cancer mortality F**	**Canada: current smoker, daily or occasional M Mean (95% CI)**	**Canada: current smoker, daily or occasional F Mean (95% CI)**
0-4	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
5-9	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
10-14	0.910 (0.140)	1.0	1.0	1.0	1.0	0 (0, 0)	0 (0, 0)
15-19	0.896 (0.154)	1.0	1.0	1.0	1.0	9.5 (7.8, 11.1)	8.9 (7.3, 10.5)
20-24	0.905 (0.158)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
25-29	0.909 (0.159)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
30-34	0.909 (0.160)	1.0	1.0	1.0	1.0	31.4 (29.3, 33.5)	22.9 (21.0, 24.8)
35-39	0.907 (0.164)	3.0	1.1	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
40-44	0.883 (0.195)	3.2	1.0	1.0	1.0	27.7 (25.1, 30.3)	18.4 (16.4, 20.4)
45-49	0.862 (0.209)	2.8	2.1	7.0	22.1	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
50-54	0.846 (0.221)	3.1	1.9	21.1	11.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
55-59	0.841 (0.219)	3.0	2.2	39.0	16.6	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
60-64	0.846 (0.213)	2.7	2.3	31.3	14.3	25.4 (23.6, 27.2)	20.5 (19.0, 22.0)
65-69	0.846 (0.210)	2.6	2.3	27.0	17.1	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
70-74	0.825 (0.221)	2.5	2.1	26.0	10.2	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
75-79	0.796 (0.243)	2.1	1.9	21.5	12.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
80-84	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
85-89	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
90-94	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)
95-99	0.704 (0.287)	1.9	1.6	13.8	7.3	10.1 (8.9, 11.2)	9.1 (8.3, 10.0)

(same information as Table 4 in Chapter 3)

6.4.9 Excess Relative Risk Model for lung cancer mortality from radon exposure

The BEIR VI exposure-age-concentration (EAC) model (NRC 1999) was used to estimate the excess relative risk per Working Level Month (ERR/WLM) by converting residential radon concentration to cumulative radon exposure, assuming an equilibrium factor of 0.4 and 7000 hours per year indoors at home lead to 1 Bq/m^3 radon exposure for 1 year equalling 0.0044 WLM at home. The model includes modifying factors for exposure-rate effect, which decreases with exposure rate over 0.5 WLM, smoking status, the smoking factor for nonsmokers is roughly double that for smokers, and attained age, which decreases with age over 55 years. Three weighted periods are used to calculate the effective exposure duration (η_t), assuming no effect from radon exposure during the 5 most recent years. Changes in radon exposure rate over the modelled lifetime can be incorporated using the following equation (Eq 2):

$$\eta_t = \Delta_{[5,14]}(t) + \theta_2 \Delta_{[15,24]}(t) + \theta_3 \Delta_{[25+]}(t) \qquad (2)$$

And $\Delta_{[a,b]}(t)$ = {10 for $t > b$; (t-a) for $a \le t \le b$; 0 otherwise}

6.4.10 Effectiveness

A 50% reduction in residential radon exposure is reported to result from the installation of passive protective measures in new construction (Woolliscroft et al. 1994). An active soil depressurization draws radon-containing soil gas from beneath the slab and exhaust it outdoors and typically results in about an 85% reduction of high initial radon levels (Health Canada 2016).

6.4.11 Quality of Life

The age-specific values (Table 21) for Health Utilities Index Mark 3 (HUI3) reported in the Canadian Community Health Survey (CCHS) for 2009-10 (Statistics Canada 2010) were used to characterize health related quality of life. The analysis is restricted to lung cancer mortality (the disutility due to lung cancer morbidity is not included) and will likely lead to results that are conservative.

6.4.12 Costs

Estimates of current construction costs for radon mitigation are listed in Table 22. The distributions of costs of radon testing and mitigation measures are assumed to be constant over the entire time horizon, which is conservative because these would be expected to continue to decrease with increasing uptake of radon mitigation.

Table 22: Costs of radon control measures

Radon Control Measure	Cost	
	mean	standard deviation
Radon test	$30	
New Construction passive preventive measures	$250	$20
New Construction active stack	$900	$30
Retrofit active stack	$1,800	$60
Maintenance for active stack (5 yrs)	$255	$15

(same information as Table 12 in Chapter 5)

6.4.13 Analysis

The economic evaluation represents the screening and mitigation of the housing with the highest radon exposures over the time horizon as the existing housing stock ages using both a Markov cohort model and a discrete event simulation model. The incremental cost effectiveness ratio (ICER) for the mitigation of existing housing is estimated relative to no specific radon control measures, at two rates of screening and mitigation, at the current rate and under a tax credit incentive, and at three radon mitigation thresholds, 200, 100 and 50 Bq/m^3. The tax credit incentive for mitigation of existing housing included is loosely modelled on the success of the ecoEnergy Retrofit Homes Program (Natural Resources Canada 2014).

A sequential analysis is conducted for the all intervention scenarios evaluated for Canada using the Markov cohort model. Passive preventive measures installed at construction in new housing are evaluated with and without screening and activation post construction of radon exposures above the mitigation threshold. The interventions based on screening and mitigation of existing housing and the interventions that combine measures in new and existing housing are included.

6.4.14 Uncertainty

The Markov cohort model is based on a Monte Carlo simulation with 10,000 samples from the distributions of all uncertainty parameters: namely, parameters relating to radon exposure, age-specific health utilities, and lung cancer mortality rates and smoking prevalence by age-group and sex. The discrete event simulated has been conducted using a simulation of 200,000 households, also sampling from the distributions of all uncertainty parameters. The cumulative incremental cost effectiveness ratios in the discrete event simulation have not yet fully stabilized, so a larger number of households will be required.

6.5 Results

The estimates of the discounted incremental cost effectiveness ratio (ICER) for interventions to screen and mitigate existing housing in Canada using the discrete event simulation model are comparable to those estimated using the Markov cohort model (Table 23); there appears to be minimal structural uncertainty associated from the choice of model used in the cost-utility analysis. The discounted ICER for mitigation of existing housing above an active mitigation threshold of 200 Bq/m^3 is 62,451 $/QALY at the current rates and 48,021 $/QALY under a tax credit incentive using the cohort model, compared to 66,421 $/QALY at the current rates and 42,788 $/QALY under a tax credit incentive using the discrete event simulation model. The discounted ICER for mitigation of existing housing above an active mitigation threshold of 100 Bq/m^3 is 58,866 $/QALY at the current rates and 51,866 $/QALY under a tax credit incentive using the cohort model, compared to 59,556 $/QALY at the current rates and 47,353 $/QALY under a tax credit incentive using the discrete event simulation model.

The cost effectiveness of these interventions is improved at the increased rate of screening and mitigation predicted to occur under the tax credit incentive. However, the optimum mitigation threshold is different at each screening and mitigation rate. At the current rate of screening and mitigation of existing of existing housing, it is slightly more cost effective at a mitigation threshold of 100 Bq/m^3. At the increased rate under the tax credit incentive, while it is slightly more cost effective at a mitigation threshold of 200 Bq/m^3. At both rates of screening and mitigation of existing housing, the lowest mitigation threshold of 50 Bq/m^3 is the least cost effective.

Table 23: Comparison of ICERs from cohort and DES models for screening and mitigation of existing housing

MODEL	ACTIVE MITIGATION THRESHOLD	Mitigation at current rate (TxxRE)		Mitigation under tax credit incentive (TxxCRE)	
		ICER ($/QALY)	discounted ICER ($/QALY)	ICER ($/QALY)	discounted ICER ($/QALY)
COHORT	200 Bq/m^3	42,494	62,451	30,422	48,021
	100 Bq/m^3	41,349	58,866	33,724	51,866
	50 Bq/m^3	56,568	79,422	48,545	73,964
DES	200 Bq/m^3	48,488	66,421	28,608	42,788
	100 Bq/m^3	44,017	59,556	31,711	47,353
	50 Bq/m^3	58,629	78,796	44,199	65,898

The sequential analysis for the cost effectiveness of all radon interventions shows that screening and mitigation of existing housing is not the recommended intervention at any cost effectiveness threshold (Table 24). The most cost effective radon intervention is the installation of passive preventive measures in new buildings. At higher levels of investment than passive preventive measures installed at construction, combinations of activation of passive preventive measures installed at construction with screening and mitigation of existing housing at different active radon mitigation thresholds are the recommended intervention scenarios.

At a radon mitigation threshold of 200 Bq/m^3, the interventions for screening and mitigation of existing housing are the interventions with the lowest discounted incremental costs versus no radon control, at $2,744,645 for current radon testing and mitigation rates and at $19,690,981 at the increased rates under the theoretical tax credit incentive. However, both of these intervention scenarios are subject to extended dominance by passive preventive measures installed at construction because the scenarios for screening and mitigation of existing housing have much lower discounted incremental QALYs than for passive preventive measures installed at construction (versus no radon control), at 44, 410 and 1,362 discounted incremental QALYs respectively. At radon mitigation thresholds of 100 and 50 Bq/m^3, the intervention scenario described by screening and mitigation of existing housing at current rates is subject to extended dominance by passive preventive measure installed at construction because it has lower discounted incremental costs and lower discounted incremental QALYs but is less cost-effective. However, the intervention scenario described by increased screening and mitigation of existing housing under a theoretical tax credit incentive is dominated by passive preventive measures at construction because it has higher discounted incremental costs and lower incremental discounted QALYs.

Table 24: Detailed sequential analysis of cost effectiveness thresholds for radon intervention scenarios in Canada

ALL INTERVENTIONS				
	Discounted incremental QALYs versus no radon control	**Discounted incremental Costs versus no radon control**	**Discounted incremental Cost per QALY gained versus no radon control**	**Sequential discounted incremental Cost per QALY Gained**
No Radon Control	0	$0	$0	$0
PN	1,362	$33,783,298	$24,809	$24,809
PN_T50ANRE	2,886	$110,553,944	$38,307	$50,367
PN_T50ANCRE	3,396	$212,961,703	$62,707	$200,723
Dominated strategies				
PN_T200ANRE	1,677	$57,351,648	$34,190	Extended dominance by PN_T100ANRE, PN_T100ANCRE, PN_T50ANRE
PN_T100ANRE	2,111	$72,679,592	$34,424	Extended dominance by PN_T50ANRE
PN_T200AN	1,438	$55,504,081	$38,604	Extended dominance by PN_T200ANRE
PN_T200ANCRE	1,875	$72,542,415	$38,684	Extended dominance by PN_T100ANRE
PN_T100AN	1,543	$67,555,368	$43,777	Dominated by PN_T200ANRE
PN_T100ANCRE	2,573	$115,146,308	$44,759	Dominated by PN_T50ANRE
T200CRE	410	$19,690,981	$48,021	Extended dominance by PN
T100CRE	966	$50,121,052	$51,866	Dominated by PN
PN_T50AN	1,789	$98,288,172	$54,945	Dominated by PN_T100ANRE
T100RE	104	$6,096,919	$58,866	Extended dominance by PN
T200RE	44	$2,744,645	$62,451	Extended dominance by PN
T50CRE	1,582	$116,993,758	$73,964	Dominated by PN_T50ANRE
T50RE	170	$13,464,444	$79,422	Extended dominance by PN

RADON MITIGATION THRESHOLD OF 200 Bq/m^3				
	Discounted incremental QALYs versus no radon control	**Discounted incremental Costs versus no radon control**	**Discounted incremental Cost per QALY gained versus no radon control**	**Sequential discounted incremental Cost per QALY Gained**
No radon control	0	$0	$0	$0
PN	1,362	$33,783,298	$24,809	$24,809
PN_T200ANRE	1,677	$57,351,648	$34,190	$74,651
PN_T200ANCRE	1,875	$72,542,415	$38,684	$76,794
Dominated strategies				
PN_T200AN	1,438	$55,504,081	$38,604	Extended dominance by AN_T200ANCRE
T200CRE	410	$19,690,981	$48,021	Extended dominance by PN
T200RE	44	$2,744,645	$62,451	Extended dominance by PN

RADON MITIGATION THRESHOLD OF 100 Bq/m^3				
	Discounted incremental QALYs versus no radon control	**Discounted incremental Costs versus no radon control**	**Discounted incremental Cost per QALY gained versus no radon control**	**Sequential discounted incremental Cost per QALY Gained**
No radon control	0	$0	$0	$0
PN	1,362	$33,783,298	$24,809	$24,809
PN_T100ANRE	2,111	$72,679,592	$34,424	$51,889
PN_T100ANCRE	2,573	$115,146,308	$44,759	$92,072
Dominated strategies				
PN_T100AN	1,543	$67,555,368	$43,777	Extended dominance by PN_T100ANRE
T100CRE	966	$50,121,052	$51,866	Dominated by PN
T100RE	104	$6,096,919	$58,866	Extended dominance by PN

RADON MITIGATION THRESHOLD OF 50 Bq/m³				
	Discounted incremental QALYs versus no radon control	**Discounted incremental Costs versus no radon control**	**Discounted incremental Cost per QALY gained versus no radon control**	**Sequential discounted incremental Cost per QALY Gained**
No radon control	0	$0	$0	$0
PN	1,362	$33,783,298	$24,809	$24,809
PN_T50ANRE	2,886	$110,553,944	$38,307	$50,367
PN_T50ANCRE	3,396	$212,961,703	$62,707	$200,723
Dominated strategies				
PN_T50AN	1,789	$98,288,172	$54,945	Extended dominance by PN_T50ANRE
T50CRE	1,582	$116,993,758	$73,964	Dominated by PN_T50ANRE
T50RE	170	$13,464,444	$79,422	Extended dominance by PN

6.6 Discussion

The choice of model used for this cost-utility analysis appears to be associated with minimal structural uncertainty because the ICER estimates derived using the Markov cohort model were comparable to those derived using the discrete event simulation. The discounted ICER for screening and mitigation of existing housing at current rates above an active mitigation threshold of 200 Bq/m^3 is 62,451 $/QALY using the cohort model and 66,421 $/QALY using the discrete event simulation model. The discounted ICER for screening and mitigation of existing housing at current rates is more cost effective using an active mitigation threshold of 100 Bq/m^3. The cost effectiveness of both intervention scenarios is improved at the increased rate of screening and mitigation expected under the theoretical tax credit incentive.

The incremental cost effectiveness ratio for screening and mitigation of existing housing in Canada can be compared to those reported for several European countries in Table 25. Due to differences between models such as residential radon distribution, smoking prevalence, time horizon, discount rate, and costs, a direct comparison is not possible. However, comparable ICERS were reported for Ireland (Pollard and Fenton 2014) and Germany (Haucke 2010). In Sweden, it was determined that screening and mitigation of existing housing was not cost effective if the mitigation threshold were to be reduced from its' current value of 200 Bq/m^3 to 100 Bq/m^3 based on a relatively short time horizon of 25 years (Svensson et al. 2018). At the low mean residential radon exposure in the UK, it was determined that screening and mitigation of existing housing was not cost effective (Gray et al. 2009).

Table 25: Cost effectiveness of radon interventions in European countries

Country (reference)	Radon Arithmetic Mean (Bq/m^3)	Discount Rate	ICERs for remediation of existing housing
Sweden (Svensson et al. 2018)	90	3%	**New housing** (reducing action level from 200 to 100 Bq/m^3) 39,000 (25,000) €/QALY – including (excluding) costs of life-years gained **Reducing action level from 200 to 100 Bq/m^3** 130,000 (90,000) €/QALY including (excluding) costs of life-years gained
Ireland (Pollard & Fenton, 2014)	89	4%	**Remediation relative to no radon control** 33,395 €/QALY (Testing funded by government) 26,672 €/QALY (Testing and remediation of social housing) 32,866 €/QALY (Requirement for radon level info upon sale)
Germany (Haucke 2010)	49	3% costs 1.5% effects	**Universal screening and mandatory mitigation of existing housing** 25,181 $€_{2008}$/QALY (for action level of 100 Bq/m^3) 38,269 $€_{2008}$/QALY (for action level of 200 Bq/m^3) 75,040 $€_{2008}$/QALY (for action level of 400 Bq/m^3)
UK (Gray et al., 2009)	21	3.5% costs 1.5% effects	**New housing** 11,400 £/QALY (Radon membrane) **Relative to no radon control (at mean radon 20 Bq/m^3)** 105,600 £/QALY (for action level of 50 Bq/m^3) 285,200 £/QALY (for action level of 100 Bq/m^3) 1,682,500 £/QALY (for action level of 200 Bq/m^3)
Norway (Stigum et al., 2003)	75	3%	**New housing and remediation of existing housing above 200 Bq/m^3** 23,000 USD/QALY

(same information as Table 19 in Chapter 5)

It was reported that screening and mitigation of existing housing is cost effective in four primary care trusts in Northamptonshire, UK, with the discounted ICERs ranging from 9,002 to 16,880 £/QALY for a discount rate of 3% (Coskeran et al. 2005). Screening and mitigation of existing housing becomes more cost effective at higher rates of remediation and when the percentage of housing above the mitigation threshold rises from 1% to 10% (Coskeran et al. 2006a). The screening and mitigation interventions for existing housing in Canada at a radon mitigation threshold of 200 Bq/m^3 and the intervention scenario described by screening and mitigation of existing housing at current rates for radon mitigation thresholds of 100 and 50 Bq/m^3 have lower discounted incremental costs but are subject to extended dominance by the installation of passive preventive measures in new housing at construction. Therefore, there might be consideration of these intervention scenarios for screening and mitigation of existing housing subject to extended dominance if lower total cost is prioritized over the optimal cost-effectiveness for jurisdictions with radon exposures similar to those of Canadians. Two approaches to reducing radon in new construction were evaluated in Brixworth, a village in Northamptonshire, UK (Coskeran et al. 2006b). It was reported that the incremental cost effectiveness ratio, discounted at 3%, for the installation of passive preventive measures in new houses that are activated above a mitigation threshold of 200 Bq/m^3 is 6,182 £/QALY and was 2,869 £/QALY for the alternative scenario of retrofitting an active depressurization system in houses that are above a mitigation threshold of 200 Bq/m^3. It was determined that a failure to activate the depressurization system in houses that were above the mitigation threshold by the home owners and a lack of maintenance resulting in less effective radon reduction in houses with an activated depressurization system by home owners were responsible for the higher ICER reported for the first scenario. Screening and mitigation of existing housing is an intervention scenario that is important to include in regions where passive preventive measures are not yet mandatory at construction.

The estimation of the cost-utility of interventions to reduce the radon exposures in existing housing over a 100-year time horizon is limited by parameter uncertainty, methodological uncertainty and structural uncertainty. Uncertainty in current lung cancer mortality rates, smoking prevalence, age-specific health related quality of life values, and costs of radon control measures were included but were assumed not to change over the time horizon of the analysis. The structural uncertainty associated with the choice of model used in the cost-utility analysis was found to be minimal. Another limitation for this analysis is that variation in the degree of maintenance of active depressurization systems for radon mitigation by home owners was not included. Continued development of the cost-utility analysis would allow exploration of changes in the housing stock over time. The sensitivity of the estimated ICERs to changes over the time horizon in the rate of construction of new housing and the projected lifetime of the housing would also be interesting to investigate. With additional data for the Canadian context, a distribution describing the effectiveness of the radon control measures and the reliability of home owners with respect to activating and maintaining an active depressurization system to reduce residential radon could be incorporated into the model. Adapting the analysis to ongoing regulatory changes and the introduction of new remediation techniques such as passive depressurization systems is expected to be important.

6.7 Conclusions

Radon remediation scenarios that describe the screening and mitigation of above- threshold radon in existing housing in Canada are estimated to be fairly cost effective. The cost-effectiveness is expected improve at increased rates of radon testing and mitigation, such as under a theoretical tax credit incentive to encourage home owners to undertake radon remediation. Structural uncertainty associated with the choice of model used for the cost-utility analysis appears minimal because the results from the use of a discrete event simulation model were comparable to those from the use of a Markov cohort model.

6.8 References

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Chapter 7 – Discussion and Conclusions

7.1 Introduction

In this last chapter, the contributions of this thesis are reviewed and their contribution as a whole to knowledge is discussed with reference to previous literature. The uncertainty associated with the results is assessed and the limitations of the studies conducted in the thesis are discussed. Suggestions are made for continuing the research into the benefits of radon remediation in the future.

An acceptable risk has been broadly defined as a non-zero baseline risk that a group of people will tolerate and for risks above which it is worth investing resources to reduce (Hunter and Fewtrell 2001). There is agreement amongst several organisations including the WHO, the EPA and EU that a 1 in 10,000 is an acceptable lifetime risk for carcinogens. The estimated baseline lifetime risk of lung cancer is roughly 1% for nonsmokers and 5 to 8% for smokers in Canada, and the lifetime relative risk of radon attributed lung cancer compared to the baseline risk is about 1.5 among nonsmokers and about 1.3 for the Canadian population at a radon exposure of 100 B/m^3 (Chen 2013). The lifetime risk for lung cancer from residential radon, a carcinogen recognized in 1988, is far higher than this baseline acceptable risk yet legislation to reduce exposures is just being introduced in Canada.

The discussion and conclusion chapter is organised into the following sections: part 7.2) an updated assessment of the burden of lung cancer mortality attributable to radon, globally and in Canada; part 7.3) the incremental cost effectiveness ratio of the gradual implementation over 100 years of potential interventions to reduce residential radon in Canada, the provinces/territories, and 17 CMAs using a Markov cohort model and a discrete event simulation model; part 7.4) an assessment of the uncertainty in the ICER estimates; part 7.5) limitations; part 7.6) future work; and part 7.7) conclusions.

7.2 Burden of Lung Cancer Associated with Residential Radon

7.2.1 Global Burden

To our knowledge, this is the first estimate of the global burden of lung cancer mortality attributed to residential radon. The estimate of the median population attributable risk (PAR) of lung cancer mortality from residential radon in 2012 for the 66 countries having representative national radon surveys were consistent, as 16.5%, 14.4% and 13.6% for the exposure-age-concentration (EAC) model (BEIR VI), the Hunter model and the Kreuzer model, respectively. The mean population attributable risk using the exposure-age-concentration model ranged from 4.2% (95% CI: 0.9, 11.7) for Japan, to 29.3% (95% CI: 22.9, 35.7) for Armenia, with a median for the 66 countries of 16.5%. Radon attributable lung cancer deaths for all 66 countries totalled 226,057 in 2012 and represent a median of 3.0% of total cancer deaths, ranging from 7.0% for Poland to 0.4% for Egypt. The results for Canada from a life-table analysis are comparable to those from the attributable fraction approach used in the main analysis, when using the BEIR VI EAC model for excess relative risk; the estimate of PAR was 16.3% (95% CI: 2.6, 32.4) from the attributable fraction approach and 14.7% (95% CI: 2.0, 30.0) from the lifetable analysis.

The global radon database from 2008 was updated with 27 recently published studies, from the 1599 papers published between 2000 and 2017 identified in a Medline database search on May 20th, 2017. The burden of disease has been estimated from the 66 countries that have representative national radon surveys, with national radon exposure determined using methodologies and measurement techniques recommended by the International Atomic Energy Agency (IAEA). Three new representative national radon surveys were conducted using alpha-track detectors, in Canada, Israel, and Turkey. For countries mostly in Eastern Europe, including Albania, Bulgaria, Montenegro, Poland, Romania, and Russia, new studies ranged from pilot studies that are being conducted in preparation for a representative national survey and studies that employ random radon sampling in more highly radon-exposed or more populated regions. There were also several new studies updating previous national radon surveys (mostly in European countries), including Ireland, the Netherlands, Spain, Sweden, Japan, and Mexico, South Korea. It is important that the global radon database be updated because representative national radon surveys are required for the accurate assessment of the associated lung cancer burden, and the extrapolation of surveys of highly radon-exposed regions to the population of a country can lead to very biased estimates.

The most populous country in the world, China, is the country with the highest estimated number of radon attributable lung cancer deaths in 2012, at 94,931 (95% CI: 8,999 - 227,236). The US is ranked 2nd, with 20,925 (95% CI: 2,137 – 51,296) radon attributed lung cancer deaths in 2012, and India is ranked 3rd, with 15,175 (95% CI: 4,211 – 26,612). The demographics of a country affect the national number of lung cancer deaths. Lung cancer mortality increases with age and the number of lung cancer deaths increased by 57% between 1990 and 2013, due primarily to the aging of the population in low and middle income countries (Naghavi et al. 2015). Countries with higher life expectancies have a greater number of lung cancer deaths. In 2012, life expectancy was 79 years in the US and 68 years in India (World Bank 2014). Even though the radon exposure is higher and the population is much greater in India than in the US, there are more lung cancer deaths attributed to radon in the US (20,925) than in India (15,175).

The estimates determined in this analysis are compared to published national estimates of PARs for eight other countries in Table 26. For both the published estimates and the ones from this analysis, those determined using the excess rate ratio derived from the pooled residential studies were roughly half those using the BEIR VI models. The published PARs determined using the excess rate ratio from pooled residential studies were closer when they were corrected for uncertainties in the exposure assessment to those using the BEIR VI EAC model in this analysis for both France (Catelinois et al. 2006), at 11% and 12%, respectively, and for Germany (Menzler et al. 2008), at 7% and 12%, respectively. Restricting the comparison of the published estimates of PAR and those from this analysis to calculations that employed the BEIR VI EAC model for excess relative risk highlights the effect of using different measures to characterize the radon exposure of a country. The studies listed in Table 1 used several different measures to define the radon exposure of the population: the arithmetic mean national exposure for the Netherlands and Sweden (Leenhouts and Brugmans 2001), the radon distribution for the UK (Health Protection Agency 2009) and the US (National Research Council 1999), while regional radon distributions were used for the estimate for France (Catelinois et al. 2006), Germany and Switzerland (Menzler et al. 2008), and South Korea (Lee et al. 2015). The published regional analysis for France reported a smaller PAR estimate (13% versus 19.4%) while the regional analysis for South Korea reported a larger PAR estimate 22% versus 16.8% when compared to the results from the national analysis used in this analysis (all using the EAC risk model). This analysis is based on a national distribution of radon exposure for each country, and the estimates from published studies that also used a national analysis were closer to this study's results, such as for the US (13.9% versus 12.5%) and for the UK (6% versus 8%).

Table 26: Comparison of national estimates of population attributable risk (PAR) of lung cancer mortality from radon according to the excess relative risk model used

	PAR Estimates (%), mean (95% CI)[a]			**Published Estimates**		
Country	**BEIR VI EAC**	**Hunter**	**Kreuzer**	**PAR (ERR model)[b]**	**Methodology**	**Source**
France	19.4 (6.2, 32.5)	17.8 (4.6, 28.4)	16.9 (8.7, 24)	13 (EAC) 5 (Euro. pooled) 2 (N Am pooled) 11 (N Am pooled cor.)	Attributable fraction, regional analysis	Catelinois et al. (2006)
Germany	14.9 (3.6, 29.8)	14.0 (3.4, 22.9)	13.1 (6.6, 18.9)	12 (EAC) 3.1 (Euro pooled) 7.3 (Euro. pooled cor.)	Period lifetable	Menzler et al. (2008)
Nether-lands	7.3 (0.9, 23.2)	5.2 (1.2, 8.9)	4.8 (2.3, 7.2)	3 (2-mutation carc.)	Cohort lifetable	Leenhouts & Brugman (2001)
Sweden	19.2 (6.0, 30.3)	22.4 (5.9, 34.9)	21.2 (11.3, `29.6)	19 (2-mutation carc.)	Cohort lifetable	Leenhouts & Brugman (2001)
Switzer-land	19.6 (1.4, 49.5)	18.2 (4.7, 29.0)	17.2 (8.9, 24.4)	8.3 (Euro. pooled)	Period lifetable	Menzler et al. (2008)
South Korea	16.8 (5.3, 29.1)	17.5 (4.4, 28.1)	16.6 (8.5, 23.6)	22 (EAC) 8.3 (Euro. pooled)	Attributable fraction, regional analysis	Lee et al. (2015)
US	12.5 (1.3, 30.6)	9.9 (2.3, 16.7)	9.3 (4.6, 13.6)	13.9 (EAC)	Period lifetable	NRC (1999)
UK	8.0 (0.6, 26.5)	5.8 (1.3, 10.1)	5.4 (2.6, 8.1)	6.0 (EAC) 3.3 (Euro. pooled cor.)	Period lifetable	HPA (2009)

This analysis investigates the results from five different models used to calculate ERR from radon, three derived from studies of miners and two derived from pooled residential studies. The three models derived from studies of miners include the BEIR VI exposure-age-concentration model (NRC 1999), the model derived from three European nested case-control studies of miners restricted to exposures <300 WLM (Hunter et al. 2013), and the model derived from a cohort of German miners having low radon exposures rates (Kreuzer et al. 2015). The studies of miners are based on cumulative radon exposure to estimate the excess relative risk per working level month (ERR/WLM). The estimates of excess relative risk derived from the European and North American pooled residential case control studies are converted from a radon concentration to cumulative exposure to enable comparison with the models based on miners. The pooled residential case control studies were designed for practical reasons to consider the residential radon exposure from 35 to 5 years (Darby et al, 2006) and 30 to 5 years (Krewski et al. 2006) prior to lung cancer, and were extended to lifetime exposure in this analysis using the estimate reported by Hunter et al. (2013) for exposures more than 25 years prior to lung cancer of ERR/WLM=0.007. The use of the BEIR VI exposure-age-concentration model for excess relative risk resulted in the highest estimate of median population attributable risk (16.5%), the excess relative risk model derived recently from the cohort of miners exposed to low doses resulted in intermediate values of median population attributable risk (Hunter: 14.4%, Kreuzer: 13.6%), and the lowest estimates resulted from the use of the excess relative risk estimates based on pooled residential studies (North Am.; 10.4%, Eur.:8.4%). It is not surprising that the lowest estimates of population attributable risk results are determined using the excess relative risk estimates determined from the pooled residential studies because the estimates of population attributable risk likely still represent an underestimate even when calculated using the higher estimates of excess relative risk based on adjustments for uncertainties in the measurement of residential radon exposure.

Consistent findings between the models used to estimate excess relative risks of lung cancer from radon exposure confirm that residential radon is responsible for a substantial proportion of lung cancer mortality worldwide. While some recent national estimates of population attributable risk have been limited to using the excess relative risk of lung cancer mortality derived from pooled residential radon studies, it is important to estimate the population attributable risk using studies of excess relative risk due to radon from both miners and residential exposures. Quantifying the uncertainty around population attributable risk estimates is necessary so that appropriate policies to reduce residential radon exposures can be adopted to decrease the associated lung cancer burden. The policy implications from basing decisions on underestimated population risks from epidemiologic studies having significant measurement error in environmental exposure and outcomes have been discussed recently by Edwards and Keil (2017). The underestimation of the risk from an environmental exposure could lead to reduced investment in preventive health interventions and reduced overall health for the population, such as experiencing easily preventable radon attributed lung cancer deaths from residential radon exposures. Conversely, the practical effectiveness of exposure reduction in a population can be lower than that reported in an epidemiologic study, if the effectiveness of the mitigation is not tested at installation, if the mitigation technology (active depressurization system) is not maintained, or if subsequent modification of the housing lowers the effectiveness of the radon mitigation. Pilot studies should be conducted prior to and radon surveys updated after the introduction of new policies to ensure that they reflect the predicted rate and effectiveness of the radon intervention in the population of interest.

7.2.2 Modifiable Burden in Canada

The modifiable burden of disease in 2012 assessed according to quality-adjusted life years (QALYs) associated with a 50% reduction and an 85% reduction in radon exposure from practical interventions for residential radon mitigation installed in new construction was assessed nationally, in the provinces/territories, and in 17 census metropolitan areas in Canada. A 50% reduction in residential radon could prevent 681 lung cancer deaths annually and an 85% reduction in residential radon could prevent 1,263 lung cancer deaths. At a discount rate of 1.5%, the gain from a 50% reduction in residential radon in the Canadian population is 15,445 QALYs over a 5 year period and the gain from an 85% reduction is 26,336 QALYs. Jurisdiction over radon in indoor air is shared between federal, provincial and municipal authorities so regional analyses were included. The highest QALYs and number of preventable radon-attributed lung cancer deaths among the provinces/territories and CMAs are for those with the highest radon exposures and largest populations. Provincial/territorial populations that would derive the greatest quality-adjusted life expectancy from radon reduction include those in the Yukon, New Brunswick, Manitoba and Saskatchewan, and the municipal populations of Sherbrooke, Regina, Winnipeg, Kelowna and Halifax. The magnitude of QALY gains in Canada estimated under the two radon mitigation scenarios is appreciable but varies considerably across provinces due to variability in indoor radon concentrations and smoking rates.

This model was based on the detailed age- and sex-specific smoking prevalence, instead of the prevalence of lifetime ever smokers. These are used with the American Cancer Society Can Prevention Study II relative risk by age and sex category to adjust lung cancer and overall mortality rates for smoking, and to specify the smoking factor used in the BEIR VI exposure-age-concentration model for the age-specific excess rate risk of lung cancer mortality from radon. The age-specific smoking prevalence for both men and women in Canada tends to rise rapidly and peak from roughly age 20 to 35, and then decrease steadily. It is important to represent the change in smoking prevalence with age because the use of lifetime ever-smoker prevalence will overestimate the smoking prevalence, which will lead to an underestimate of the radon attributed lung cancer mortality. The age- and sex-specific smoking prevalence is reported for current smoker, daily and occasional, and nonsmoker and the CPS II relative risk by age and sex category compares current smoker, daily and occasional, with lifelong nonsmoker. A population consists of former smokers in addition to current smokers and lifelong nonsmokers. Recent research reported that the relative risk of former smokers decreases rapidly with time since quitting and is close to that of lifelong nonsmokers after 20 years (Kenfield et al. 2008; Pesch et al. 2012). This analysis modelled smokers who quit more than 20 years prior as lifelong nonsmokers, and conservatively assumed a linear decrease in relative risk over a 20 year period for former smokers when age- and sex-specific smoking prevalence decreases with increasing age (Kenfield et al. 2008; Pesch et al. 2012).

The number of radon attributable lung cancer deaths that might be prevented by theoretical reductions in residential radon were estimated for Canada (Al-arydah 2018; Chen et al. 2012) and for Ontario (Peterson et al. 2013). A direct comparison between these published studies and this analysis cannot be made because the theoretical mitigation scenario was different for each study. The BEIR VI exposure-age-concentration model for excess relative risk was included in all three studies. The two remediation scenarios assessed in this analysis resulted in larger reductions in radon than the interventions considered in the other published studies. Both interventions in this analysis included preventive measures installed at construction that reduce all radon exposures in the distribution; the reduction per house is lower but the total reduction for the population is much larger. Other studies investigated the effect of reducing radon levels in houses above specific active mitigation thresholds to outdoor levels. Therefore, the annual number of radon attributed lung cancer cases that could be prevented by the remediation scenarios modelled in this analysis are higher, as expected, at 681 (95% CI: 100 – 1,284) and 1,263 (95% CI: 171 - 2,571), for reduction of radon by 50% and 85% respectively. Remediation of houses with radon above 800 (200, 100) Bq/m^3 would result in 90 (927, 1704) deaths averted annually, respectively, out of a total of 3261 lung cancer deaths attributed to residential radon in Canada (Chen et al. 2012). The concave shape of plots of increasing population attributable risk with increasing action/threshold for radon remediation in existing housing, in all five Canadian provinces assessed, similarly demonstrates that greater relative benefit would be derived for lower action/threshold levels for radon mitigation (Al-arydah 2018). In this analysis for Ontario, 195 (95% CI: 29-399) lung cancer cases could be prevented annually from a 50% reduction in residential radon and 360 (95% CI: 50-797) cases could be prevented annually from an 85% reduction. Peterson et al. (2013) estimated the number of radon-related lung cancer deaths that could be prevented in Ontario for the theoretical reduction of residential radon levels over the active mitigation threshold to background outdoor levels; if all Ontario homes with radon levels over 200 (150, 100, 50) Bq/m^3 were remediated to background outdoor levels, 91 (149, 233, 389) radon-related lung cancer deaths, respectively, could be prevented. For Ontario, the largest reduction in radon would result from the theoretical reduction of all residential radon over 50 Bq/m^3 to background levels, and the corresponding estimate of 389 preventable deaths would represent 46% of estimated lung cancer deaths in Ontario attributed to radon (Peterson et al. 2013).

Several measures may be used to assess the burden of a disease. Premature mortality caused by a disease can be characterized by the number of years of life lost (YLL) qualified by an age-weight, and the years lived with disability (YLD) is qualified using a disability weight, having a value between 0 for perfect health and 1 for death. Quality-adjusted life years (QALYs) use a weight for each year of life using a preference-based assessment of the health-related quality of life, with a value between 1 for perfect health and 0 for death.

The burden of radon attributed lung cancer mortality in Canadian provinces was estimated using quality-adjusted life years (QALYs) in this analysis and using years of life lost (YLLs) and years lived with disability (YLDs) by Al-arydah (2018). Again, the scenarios were different, the modifiable burden of radon attributed lung cancer mortality was assessed in this analysis while the total burden attributed to radon attributable lung cancer mortality was assessed by Al-arydah (2018). The results of the two studies can be compared because the BEIR VI exposure-age-concentration model for excess relative risk of lung cancer mortality from radon was used in both analyses. In the highly radon exposed Manitoba population, the YLL to radon attributed lung cancer mortality over the four year period ending in 2009 was between 2528 and 5473 years for men and between 2,459 and 5,780 years for women. In Quebec, the YLL to radon attributed lung cancer mortality over four years was between 26,678 and 58,129 years for men and between 23,118 and 53,310 years for women. In this analysis, the QALYs gained for an 85% reduction in residential radon over a five year period was 3,827 (95% CI: 402 – 9,587) and QALYs discounted at 1.5% was 1,508 (95% CI: 174 – 3,777) for the 2012 Manitoba population. The QALYs gained for an 85% reduction in residential radon over a five year period was 17,857 (95% CI: 1,141 – 62,779) and QALYs discounted at 1.5% was 7,045 (95% CI: 450 – 24,771) for the 2012 Quebec population.

Lung cancer was ranked as a leading cause of YLLs in 2010 in Canada, second only to ischemic heart disease, with the number of YLLs due to lung cancer increasing by 21% from 1990 to 2010 and resulting in lung cancer representing 8.8% of the total years of life lost in Canada in 2010 (IHME 2013). Quality-adjusted life years have more recently been identified as the preferred metric for assessment of the health benefits of interventions in Canada by the Canadian Agency for Drugs and Technologies in Health (CADTH). Health technology assessments in Canada increasingly report cost effectiveness ratios ($/QALY) to make health system decision making more explicit and to improve transparency and public involvement (Jaswal 2013). It is useful to estimate QALYs for the evaluation of incremental cost utility ratios, which allow for the comparison of interventions to reduce residential radon exposure with other medical interventions. Incremental cost effectiveness ratios can also inform discussions about balancing prevention with treatment of lung cancer.

A global analysis recently quantified the increased mortality and lung cancer from environmental exposure to particulate air pollution (Evans et al. 2013) and the gain in quality-adjusted life expectancy associated with a uniform reduction in sulfate air pollution in Canada was estimated to be 20,960 QALYs discounted at 5% and 25,520 QALYs undiscounted (Coyle et al. 2003). For Canada, the undiscounted period QALY gain for a 50% (85%) reduction in residential radon exposure was about 1.5 (2.5) times the undiscounted annual QALY gain from a 1 $\mu g/m^3$ reduction in sulfate air pollution. The gain from reducing population exposure to air pollution is higher than that from reducing radon because both sulfate and particulate air pollution are associated with cardiovascular mortality in addition to lung cancer mortality, with ischemic heart disease contributing the largest number of YLLs and stroke the third largest number of YLLs to premature mortality in Canada (IHME 2013).

It is important to note that the greatest population health gain results from preventive measures installed at construction because radon levels are reduced for all values in the distribution. It is the only practical radon remediation strategy that reduces the lower and mid-range exposures that constitute the majority of the values in the lognormal distribution that describes residential radon exposures in Canada. It was estimated that 73% of lung cancer deaths attributable to residential radon exposure in Ontario (Peterson et al. 2013) and 85% in the UK (Gray et al. 2009) would result from exposures below 100 Bq/m^3. The passive preventive measures and active depressurization systems evaluated in this analysis for new construction reduce the smaller risks experienced by the middle of the distribution and prevent a far greater number of cases of a disease than adopting a strategy preventing only the highest risk, described by Rose (2008) as a "targeted rescue operation for vulnerable individuals" at the tail of the distribution. It is also significant from a policy perspective that it is more practical to enforce changes in the building code according to which new construction is regulated than to enforce radon testing and mitigation in existing housing because of the 3 month winter time period required for reliable measurement of residential radon.

7.3 Economic Evaluation of Interventions to Reduce Burden from Residential Radon in Canada

The novelty of this research is the conceptualization of this complex problem into an analytic framework using both a Markov cohort model and a discrete event simulation that is based on households rather than individuals. The models were based on data for Canada and regions involving regional radon distributions in Canada, the 2012 populations, and the age- and sex-specific risk of overall and lung cancer mortality adjusted for smoking. The BERI VI exposure-age-concentration model was used to estimate the age-specific excess risk rate of residential radon exposure for lung cancer mortality, the Canadian health utility values were used for all regions in Canada, and the uptake by house-owners of any voluntary radon mitigation recommendations were estimated for several funding conditions. The cost-utility analysis describing the gradual implementation over the 100 year time horizon of radon prevention in new housing and radon screening and mitigation in existing housing was specified using 16 intervention scenarios compared to the installation of passive preventive radon measures at construction, the current legal requirement in the majority of jurisdictions in Canada. The gradual implementation over the 100 year time horizon of radon screening and mitigation in existing housing relative to no specific radon control for Canada is applicable for jurisdictions where no radon control is required in new housing. The use of both a Markov cohort model and a discrete event simulation for the second cost-utility analysis enabled the structural uncertainty associated with the model structure to be assessed. A simplified housing model representing dwellings occupied by usual residents was constructed from ten years of data to smooth out annual fluctuations in the growth rate for housing stock and new construction, with demolitions assumed to make up the difference for dwellings occupied by usual residents between new construction and housing stock growth (ie housing renewal). In the discrete event simulation model, the time to event was simulated for the lifetime of each housing unit, for the time to mitigation for each intervention scenario, and for the lifetime of each resident in the house. Additional data on the age of current housing in Canada was used in the discrete event simulation model.

7.3.1 Cost-utility analysis of practical radon interventions relative to preventive radon control in new housing for Canada, the provinces/territories, and 17 CMAs

The passive preventive measures installed in new buildings at construction outlined in the National Building Code (NBC) of Canada are very cost effective in all regions of Canada, even those with the lowest radon exposures. The provisions addressing radon prevention in new housing in the NBC require a rough-in for a future sub-slab radon removal system and enhanced sealing including the use of a radon membrane under the foundation slab. The incremental cost effectiveness ratio for passive preventive measures installed in new construction compared to no specific radon control ranges from a mean (standard error) of 5,657 (10) $/QALY for the Yukon to 53,163 (106) $/QALY for Nunavut, with a mean of 24,809 (231) $/QALY for Canada overall. Although it has yet to be adopted in all provincial building codes across Canada, it is estimated that 453 lung cancer deaths would be prevented if the preventive radon measures specified in the National Building Code of Canada were a legal requirement for all new housing in Canada.

A series of cost effective radon interventions are identified at increasing cost effectiveness thresholds from sequential analyses of 16 radon intervention scenarios combining preventive measure in new housing and mitigation of existing housing compared to the baseline scenario. The baseline scenario is defined by the installation of passive preventive measures in new construction (abbreviated as PN, for Preventive measures in New housing). The baseline scenario (PN) is the most cost effective radon intervention in all regions of Canada. Table 27 shows the results of the sequential analyses for Canada and the regions where radon intervention is most cost effective for mitigation thresholds of 200 Bq/m^3 and 100Bq/m^3. The most cost effective radon intervention scenario relative to the baseline PN scenario for all

Table 27: Cost effectiveness thresholds for radon intervention scenarios based on sequential analysis of discounted ICERs for active radon mitigation thresholds of 200 Bq/m^3 and 100 Bq/m^3 for Canada, New Brunswick, Manitoba, Winnipeg, and the Yukon

Region	Active radon mitigation threshold	
	200 Bq/m^3	100 Bq/m^3
Canada	PN for λ < 74,651 PN T200ANRE : 74,651< λ < 76,794 PN T200ANCRE : 76,794 < λ < 344,749 AN T200CRE : λ > 344,749	PN : λ < 51,889 PN T100ANRE : 51,889 < λ < 92,072 PN T100ANCRE : 92,072 < λ < 428,362 AN T100CRE : λ > 428,362
NB	PN : λ < 28,680 PN T200ANRE : 28,680 < λ < 113,261 PN T200ANCRE : 113,261 < λ < 322,866 AN T200CRE : λ > 322,866	PN : λ < 30,733 PN T100ANRE : 30,733 < λ < 133,530 PN T100ANCRE : 133,530 < λ < 445,726 AN T100CRE : λ > 445,726
MB	PN : λ < 26,920 PN T200ANRE : 26,920 < λ < 73,330 PN T200ANCRE : 73,330 < λ < 162,385 AN T200CRE : λ > 162,385	PN : λ < 27,558 PN T100ANRE : 27,558 < λ < 85,965 PN T100ANCRE : 85,965 < λ < 233,009 AN T100CRE : λ > 233,009
Winnipeg	PN : λ < 10,338 PN T200ANRE : 10,338 < λ < 32,112 PN T200ANCRE : 32,112 < λ < 66,754 AN T200CRE : λ > 66,754	PN : λ < 12,714 PN T100ANRE : 12,714 < λ < 51,510 PN T100ANCRE : 51,510 < λ < 99,705 AN T100CRE : λ > 99,705
YT	PN : λ < 15,068 PN T200ANRE : 15,068 < λ < 31,323 PN T200ANCRE : 31,323 < λ < 86,439 AN T200CRE : λ > 86,439	PN : λ < 15,801 PN T100ANRE : 15,801 < λ < 36,547 PN T100ANCRE : 36,547 < λ < 118,710 AN T100CRE : λ > 118,710

Notes: PN – baseline passive preventive measures installed at construction, PN T200ANRE (PN T100ANRE) – activation of passive preventive measures in new housing and mitigation of existing housing above radon mitigation threshold above 200 (100) Bq/m^3, PN T200ANCRE (PN T100ANCRE) – activation of passive preventive measures in new housing and mitigation of existing housing above radon mitigation threshold of 200 (100) Bq/m^3, AN T200CRE (AN T100CRE) – active depressurization in all new housing and mitigation of existing housing above mitigation threshold of 200 (100) Bq/m^3.

regions except those with very low radon exposures is the combination of the activation of preventive measures in new housing with the mitigation of existing housing at current testing and mitigation rates at each of the three active radon mitigation thresholds (200 Bq/m^3, 100Bq/m^3, and 50 Bq/m^3). For populations where this radon intervention (abbreviated as PN T200ANRE, PN T100ANRE, and PN T50ANRE) is most cost effective, it is recommended for cost effectiveness thresholds below about 50,000 $/QALY. These populations include Nova Scotia, New Brunswick, Quebec, Manitoba, Saskatchewan, the Yukon, the Northwest Territories, St. John’s, Halifax, St. John, Quebec City, Sherbrooke, Montreal, Ottawa-Gatineau, Kingston, Windsor, Winnipeg, Saskatoon, Regina, Calgary, and Kelowna. For the regional populations with the highest radon exposures, increasing the rate of mitigation of existing housing by lowering the mitigation threshold or by introducing a tax credit (abbreviated as PN T200ANCRE, PN T100ANCRE, PN T50ANCRE) is also recommended at cost effectiveness thresholds below about 50,000 $/QALY. The most comprehensive scenario for radon exposure reduction, active depressurization in all new housing and in existing housing above the radon mitigation threshold (abbreviated as AN T200CRE, AN T100CRE, AN T50CRE), is generally not cost effective.

The results of five health economic evaluations conducted in European countries to estimate the cost per quality-adjusted life year gained for radon interventions scenarios are listed in Table 28: in Sweden (Svensson et al. 2018), Ireland (Pollard & Fenton 2014), the UK (Gray et al. 2009), Germany (Haucke 2010) and Norway (Stigum et al. 2003). However, only in Norway was a radon intervention scenario evaluated that also combined the prevention of radon ingress in new housing with the screening and mitigation of existing housing. This scenario is cost effective in both countries compared to no specific radon control, having an ICER of 23,000 USD/QALY using a radon mitigation threshold of 200 Bq/m^3 discounted at 3% for Norway (in 2003), and having an ICER of 34,424 $/QALY and 38,307 $/QALY discounted at 1.5% in Canada for current radon testing and mitigation rates using radon mitigation thresholds of 100 Bq/m^3 and 50 Bq/m^3, respectively. For most regional populations in Canada, the combination of activation of passive preventive measure in new housing and screening and mitigation of existing housing at current radon testing and mitigation rates relative to passive preventive measures in new housing were found to be cost effective.

Table 28: Cost effectiveness of radon interventions in European countries

Country (reference)	**Radon Arithmetic Mean (Bq/m³)**	**Discount Rate**	**ICERs**
Sweden (Svensson et al. 2018)	90	3%	**New housing** (reducing action level from 200 to 100 Bq/m³) 39,000 (25,000) €/QALY – including (excluding) costs of life-years gained **Existing housing** (reducing action level from 200 to 100 Bq/m³) 130,000 (90,000) €/QALY – including (excluding) costs of life-years gained
Ireland (Pollard & Fenton, 2014)	89	4%	**New housing** 12,524 €/QALY (Radon membrane) 81,866 €/QALY (Active stack) **Remediation of existing housing (action level 200 Bq/m³)** 33,395 €/QALY (Testing funded by government) 26,672 €/QALY (Testing and remediation of social housing) 32,866 €/QALY (Requirement for radon level info upon sale)
Germany (Haucke 2010)	49	3% costs 1.5% effects	**Universal screening and mandatory mitigation of existing housing** 25,181 $€_{2008}$/QALY (for action level of 100 Bq/m³) 38,269 $€_{2008}$/QALY (for action level of 200 Bq/m³) 75,040 $€_{2008}$/QALY (for action level of 400 Bq/m³)
UK (Gray et al., 2009)	21	3.5% costs 1.5% effects	**New housing** 11,400 £/QALY (Radon membrane)
Norway (Stigum et al., 2003)	75	3%	**New housing and remediation of existing housing above 200 Bq/m³** 23,000 USD/QALY

In Sweden, screening and mitigation of new and existing housing at an action level of 200 Bq/m³ is recommended, and it was determined in a recent analysis that it was cost effective to reduce the action level from 200 to 100 Bq/m³ for screening and mitigation of new housing but not for existing housing (Svensson et al. 2018). The ICER was 39,000 (25,000) €/QALY for new housing and was 130,000 (90,000) €/QALY for existing housing QALY – including (excluding) costs of life-years gained, using a discount rate of 3% and a time horizon of 25 years (Svensson et al. 2018). In Canada, the ICERs for reducing the active radon mitigation threshold from 200 to 100 Bq/m^3 are estimated for intervention scenarios that combine the gradual implementation throughout the housing stock of the activation of new housing and mitigation of existing housing. Excluding costs for life-years gained, these ICER estimates are 35,327 $/QALY at the current rates (PN T100ANRE relative to PN T200ANRE) and 61,098 $/QALY at the increased rate under the tax credit incentive (PN T100ANCRE relative to PN T200ANCRE). Despite differences in the analyses, the estimates for Sweden and Canada are roughly comparable. The lower ICER estimates for Canada result from the lower discount rate, longer time horizon and gradual implementation used in this analysis.

Similar conclusions were drawn from the other European studies that have conducted health economic evaluations of population wide interventions to reduce residential radon exposure, although direct comparison is not possible because mitigation of existing housing was evaluated separately from prevention in new housing. In Ireland or the UK, installing a radon membrane and sealing joints and cracks was determined to be cost effective in new housing while screening and mitigation scenarios for existing housing were not found to be cost effective (Pollard & Fenton 2014; Gray et al. 2009). For all populations in Canada, passive radon prevention measures installed in new construction relative to no radon control are cost effective. In the UK, Germany, and Norway, screening and mitigation scenarios were more cost-effective at lower action levels (Gray et al. 2009; Haucke 2010; Stigum et al. 2003). Similarly, intervention scenarios that include screening and mitigation of existing housing were found to be more cost effective at lower mitigation thresholds for Canada overall and many regional populations.

Two policy options can be used to promote radon prevention and mitigation in housing, mandatory measures and incentives. In Canada, the home energy retrofit tax credit is an example of an incentive leading to the widespread adoption of new policies. Mandatory measures can be interpreted as punitive. Incentives have been used to make a choice that is better in the long term and more appealing to consumers, which is sometimes called a nudge (Thaler and Sunstein 2003). In the context of radon mitigation, loss aversion is a behaviour that can be described by being guided by worry about potential future loss and uncertainty about future benefits. It is important to frame choices to help home owners balance the up-front costs of radon mitigation with future benefits, and a tax credit can present mitigation as a bargain instead of a potential loss (Gillingham and Palmer 2013). A pilot project in a city with high radon such as Regina or Winnipeg would be a good way to investigate home owner response to a tax credit incentive.

The cost effectiveness of interventions to reduce radon can be compared to lung cancer screening and treatment programs in Canada. Two health economic evaluations were recently conducted for a lung cancer screening program targeted at people identified as being at high risk of lung cancer in Canada and in Ontario, reporting ICER estimates ranging from 20,724 to 32,352 $/QALY and an ICER estimate of 32,476 $/QALY, respectively (Cressman et al. 2017; Thao 2014). These were based on a 6 year time horizon and discount rates ranging from 3% to 5%. A lung cancer screening program targeted at smokers in Canada but based on a longer time horizon of 20 years and a discount rate of 3% estimated an incremental cost effectiveness ratio of 52,000 $/QALY compared to no screening (Goffin et al. 2015). The most cost effective radon intervention scenario relative to the baseline PN scenario for many provincial populations in Canada is comparable to the lung cancer screening program based on the longer time horizon. The activation of passive preventive measures in new housing and mitigation of above threshold in existing housing becomes the recommended scenario for Canada overall at a cost effectiveness threshold of 51,889 (50,367) $/QALY at a mitigation threshold of 100 (50) Bq/m^3. For Manitoba, this radon intervention is cost effective at all three radon mitigation thresholds: at cost effectiveness thresholds between 26,920 and 73,330 $/QALY at an active radon mitigation threshold of 200 Bq/m^3, between 27,558 and 85,965 $/QALY at an active radon mitigation threshold of 100 Bq/m^3, and between 31,819 and 248,270 $/QALY at an active radon mitigation threshold of 50 Bq/m^3. For Ontario, this scenario is less cost effective: for cost effectiveness thresholds between 71,334 and 109,678 $/QALY and between 64,251 and 223,272 $/QALY at active radon mitigation thresholds of 100 Bq/m^3 and 50 Bq/m^3, respectively. It is important to note that the ICERS for radon interventions are conservative because unlike the lung cancer screening programs, they do not include the costs and effects of lung cancer morbidity.

Treatment of lung cancer using expensive new genotype-specific drugs was also investigated by Thao (2014), and the ICER was estimated to be 32,913 $/QALY for Gefitinib as firstline treatment in EGFR+ patients and 111,851 $/QALY for Gefitinib and Crizotinib treatment in EGFR+ and ALK+ patients. Screening people at high risk of lung cancer enables earlier treatment and prevention of lung cancer results in gains in quality-adjusted life expectancy and reductions in lung cancer treatment costs. It was determined that the inclusion of higher non-curative costs, such as the targeted chemotherapy drugs currently being considered in Canada that cost two to ten times more than the drugs currently in use, would make the high risk lung cancer screening program based on the 6 year time horizon for Canada much more cost effective and potentially cost-saving. Similarly, should targeted chemotherapy drugs be approved, investment in lung cancer prevention using residential radon interventions would also be considered highly cost effective if the analysis was extended to include costs and effects of lung cancer morbidity.

7.3.2 Cost-utility analysis of practical interventions to reduce residential radon in existing housing in Canada

Two different model structures were used to conduct the cost-utility analyses for the mitigation of existing housing in Canada relative to no radon control measures, a Markov cohort model and a discrete event simulation model. Markov cohort models are a common form of decision-analytic model used for health economic evaluation. A discrete event simulation model allows the history of an individual to be incorporated into the progression along the time horizon, by calculating the length of time an individual is in each state. By contrast, the assumption in a Markov model is that the transition probabilities, of moving from one state to another, do not depend on the past of the individual or the time spent in a given state. The main disadvantages of using microsimulation models is the much larger amount of input data required and the increase in computer power/time needed to generate results.

The discounted incremental cost effectiveness ratios for screening and mitigation of existing housing in Canada estimated using the discrete event simulation model are very comparable to those estimated using the Markov cohort model (Table 29). It is more cost effective when the rate of screening and mitigation is increased under the theoretical tax credit incentive. It is slightly more cost effective using a mitigation threshold of 100 Bq/m^3 at the lower current rate of mitigation, but this situation is reversed and it is slightly more cost effective using a mitigation threshold of 200 Bq/m^3 under the tax credit incentive. At the current rate of mitigation, the discounted ICER is 62,451 (66,421) $/QALY at a mitigation threshold of 200 Bq/m^3 and 58,866 (59,556) $/QALY at a mitigation threshold of 100 Bq/m^3, for the cohort (DES) models respectively. At the increased rate under the tax credit incentive, the discounted ICER is 48,021 (42,788) $/QALY at a mitigation threshold of 200 Bq/m^3 and 51,866 (47,353) $/QALY at a mitigation threshold of 100 Bq/m^3. At both rates of screening and mitigation of existing housing, the lowest mitigation threshold of 50 Bq/m^3 is the least cost effective.

Table 29: Comparison of ICERS from cohort and DES models for screening and mitigation of existing housing

MODEL	Active mitigation threshold	Mitigation at current rate		Mitigation under tax credit incentive	
		ICER ($/QALY)	discounted ICER ($/QALY)	ICER ($/QALY)	discounted ICER ($/QALY)
COHORT	**200 Bq/m^3**	42,494	62,451	30,422	48,021
	100 Bq/m^3	41,349	58,866	33,724	51,866
	50 Bq/m^3	56,568	79,422	48,545	73,964
DES	**200 Bq/m^3**	48,488	66,421	28,608	42,788
	100 Bq/m^3	44,017	59,556	31,711	47,353
	50 Bq/m^3	58,629	78,796	44,199	65,898

The sequential analysis compared to no specific radon control for new construction demonstrates that screening and mitigation of existing housing is less cost effective than the installation of passive preventive measures in new construction. For Canada, the screening and mitigation of existing housing at all mitigation thresholds at both the current rate and under a tax credit incentive is subject to extended dominance by the baseline preventive measures, having lower costs than the baseline scenario but higher ICERS. Only at the increased rate under the tax credit incentive at a mitigation threshold of 100 Bq/m^3 is the cost higher than the baseline scenario, which results in a situation of extended dominance by the baseline scenario. This is consistent with the estimates for combinations of radon interventions that are based on the higher rate of screening and mitigation of existing housing under the tax credit incentive having higher ICERs than the corresponding combinations that are based on the lower current rate of screening and mitigation of existing housing.

The incremental cost effectiveness ratio for screening and mitigation of existing housing has been reported for several European countries in Table 28. These studies report comparable results to the estimates for Canada, but due to differences between models such as residential radon distribution, smoking prevalence, time horizon, discount rate, and costs, a direct comparison is not possible. Comparable ICERS were reported for Ireland (Pollard and Fenton 2014) and Germany (Haucke 2010) because a higher mean radon exposure was balance by lower rates of testing and mitigation for Ireland, whereas lower discount rates and universal screening and mandatory mitigation were balanced by a lower mean radon exposure in Germany. The ICERS are comparable to those for Canada, which are a bit lower for the higher mitigation rate under the tax credit incentive and a bit higher for the low current rate of mitigation. In Sweden, it was determined that screening and mitigation of existing housing was not cost effective if the mitigation threshold were to be reduced from its' current value of 200 Bq/m^3 to 100 Bq/m^3 based on a relatively short time horizon of 25 years (Svensson et al. 2018). In the UK it was determined that screening and mitigation of existing housing was not cost effective (Gray et al. 2009), but that is expected given the low mean residential radon exposure. In four primary care trusts in Northamptonshire in the UK, it was determined that screening and mitigation of existing housing is cost effective using a discount rate of 3%, reporting discounted ICERs ranging from 9,002 to 16,880 £/QALY (Coskeran et al. 2005). As in the other studies, further analysis showed that screening and mitigation of existing housing becomes more cost effective at higher rates of remediation (Coskeran et al. 2006a).

The discrete event simulation model is flexible so that changes in the housing stock over time can be explored. Ninety percent of the housing in Canada dates from the postwar boom that was the result of the baby boom and government policies designed to increase and expand home ownership in the growing urban population (Hulchanski 2003). The Canada Mortgage and Housing Corporation (CMHC) published catalogues of designs for single detached dwellings, small starter homes appropriate for first time home buyers, assembled from submissions made to its Small House Design Scheme (Teodorescu 2012). Many federal and provincial tax incentives continue to exist to assist home owners to renovate, such as energy efficiency tax incentives, or for elderly home owners to make their houses accessible as mobility challenges increase in the aging population (Petramala 2013). Many renovations are completed by current home owners expanding their space by finishing the basement or adding an extension. For the first time in Canada, from mid-2016 through 2017, the largest investment in residential construction resulted from spending on renovations. In the fourth quarter of 2017, spending on renovations represented 42% of the total residential construction investment (Statistics Canada 2018b). Based on the current situation, the screening and mitigation of existing housing is not the most cost effective radon intervention scenario. Investment in radon prevention, beyond passive preventive measures installed at construction, is recommended using a combination of prevention in new housing and mitigation of existing housing. However, should the current trends of decreasing residential construction investment in new construction and increasing investment in renovations continue, then the rate of housing renewal will continue to decrease and the screening and mitigation of existing housing will be required to reduce the residential radon exposures of the population.

7.4 Assessment of Uncertainty

Many valid models can be used to calculate statistics such as the incremental cost effectiveness ratio that are used to help make decisions involving health care interventions. Models produce estimates that vary depending on the underlying approximations employed and it is useful to assess the uncertainty associated with a modelled statistic. Three main categories of model uncertainty have been identified, including parameter uncertainty, methodological uncertainty, and structural uncertainty.

It is recommended that parameter uncertainty be addressed by representing a parameter using a distribution that is sampled during a probabilistic analysis. In this study, distributions were used for the following parameters: residential radon exposure, adult smoking prevalence for men and for women, age-specific health utilities and lung cancer mortality rates. A lognormal distribution was fitted to the residential radon data, a normal distribution was assumed for radon mitigation costs, while a normal distribution was reported for smoking prevalence and lung cancer mortality rate. These distributions are sampled 10,000 times in the Monte Carlo simulation for the cohort model. The distributions have been sampled 400,000 times in the discrete event simulation model.

The measured radon distribution can be considered to be a sample of the true radon distribution and subject to uncertainty. Adjustment for annual variation in residential radon measurement was also made for the radon distributions used in the model for Canada, the provinces/territories, and 17 census metropolitan areas. Estimates of uncertainty from the year-to-year variation have been reported from repeated annual radon measurement in a subset of dwellings (Darby et al. 1998, 2006b). A comparison was made of the variation in the radon distributions fitted to radon measurements for the 33 CMAs in the CMA survey with those from the national survey conducted two years prior to yield an estimate of the uncertainty from annual variation. The radon distributions fitted to the radon measurements are adjusted by subtracting the uncertainty from annual variation from the measured variation on the log scale for all regions in Canada. As in other studies, it was assumed that the distribution of the natural logarithm of the annual radon measurements in a given area was normally distributed and that this variability is independent of the radon level (Darby et al. 2006b; Gray et al. 2009).

Methodological uncertainty, in this thesis, is assessed for the model used to determine the excess relative risk model for lung cancer from radon exposure in this thesis. Many models that quantify the excess relative risk of lung cancer from long term radon exposure have been published and they provide an opportunity to assess the uncertainty in the estimates of the population attributable risk of lung cancer mortality attributed to radon exposure. The models based on cohorts of miners and those based on pooled residential case control studies complement each other and it is important to consider all the published models to determine the burden of lung cancer associated with residential radon exposure. The studies of miners were characterized by far superior radon exposure assessment and the residential studies were characterized by detailed assessments of smoking status of participants and included women as well as men. The measurement error in the radon exposure assessments upon which the pooled residential studies were based resulted in a significantly underestimated excess relative risk of lung cancer associated with radon exposure, and might still represent an underestimate even after adjustments were made to reduce the exposure measurement error.

This methodological uncertainty is explored in the estimation of the global burden of lung cancer mortality attributable to radon exposure by comparing five excess relative risk models, three derived from studies of miners and two derived from pooled residential studies. The median population attributable risk estimate from the North American pooled residential study model of excess relative risk is two-thirds the value of the median population attributable risk estimate from the use of the BEIR VI exposure-age-concentration model. It is reassuring that estimates of population attributable risk derived from the pooled residential studies after restriction of data to the better radon exposure measurement were comparable to (though lower than) those derived from the cohort studies of miners. In this analysis, use of the BEIR VI exposure-age-concentration model for excess relative risk resulted in the highest estimate of median population attributable risk (16.5%), use of the ERRs based on pooled residential studies resulted in the lowest estimates (North Am.; 10.4%, Eur.:8.4%), while the recently derived excess relative risk models based on miners exposed only to low doses resulted in intermediate values of population attributable risk (Hunter: 14.4%, Kreuzer: 13.6%). Lastly, conservative estimates of excess relative risk from the miners exposed only to low doses were selected in this analysis; higher estimates of excess relative risk were reported in both studies from a further restriction of data to lower cumulative radon exposures but were associated with larger uncertainty.

The BEIR VI EAC model is the oldest model (National Research Council 1999) using coefficients that were derived from fitting the model to the data from 11 cohorts of miners (Krewski et al. 1999). The BEIR VI model is based on extensive data (2,700 lung cancer deaths in 68,000 miners contributing nearly 1.2 million person-years of observation) and is still the most complete model, including factors for smoking status, time since exposure, radon exposure rate, and attained age. The BEIR VI model has been fitted to the lowest radon exposure rate data, and the model was found to have the same fit for radon levels typical of residential settings as it does for the full range of radon exposures experienced by underground miners.

The extrapolation of the higher radon exposures of miners evaluated in the BEIR VI model to the lower dose residential radon setting may introduce uncertainty, and so the recent Hunter and Kreuzer models are based on low radon exposure rates and low cumulative doses that approximate those resulting from lifetime residential exposures were also included. The Kreuzer cohort was characterized by miners having a mean employment duration of 10 years, with follow up from 1960 to 2008 (mean duration of follow up of 32 years). Further restriction of the Hunter and Kreuzer models to lower cumulative radon exposures resulted in higher risk estimates for both, however in order to be conservative, these were not selected for this analysis due to the much smaller number of person-years of observation upon which they were based.

Concerns have been raised about generalizing the results of studies of miners to the general population because there are significant differences between the subgroup of miners and the general population due to both characteristics of miners and to the range of exposures they were subjected to in the mines. It was reported that the estimate of excess relative risk of lung cancer from radon decreased when co-exposure to diesel engine exhaust was included as a confounder in a reanalysis of the 11 cohorts used for the BEIR VI models, using both an additive and a multiplicative model (Cao et al. 2017). However, an investigation into possible confounding with radon was conducted using the German Wismut miner cohort from co-exposure to external gamma radiation, long-lived radionuclides, arsenic, fine dust and silica dust. When included in an additive manner, it was reported that these covariables had only a minor confounding influence on the estimate of ERR/WLM of lung cancer from radon (Walsh et al. 2010). Healthy worker bias was identified in the Colorado plateau uranium miners cohort that resulted in an underestimated ERR/WLM if adjustment was not made in the analysis for time-varying confounding by employment status (Keil et al. 2015). Further analysis of miner cohort studies have identified that lack of adjustment for confounders can result in overestimation or underestimation of the excess relative risk of lung cancer mortality from radon exposure.

The studies of miners were characterized by far superior radon exposure assessment, based on annual measurements of radon for each year a miner was exposed, whereas the residential studies relied on only one or two measurements for the entire 30 year period of exposure considered. Any degree of residential mobility has a severe impact on the precision of residential radon exposure in the pooled case-control studies. The excess relative risk per 100 Bq/m^3 radon increased from 8% to 16% when the European analysis was adjusted for the random uncertainties from using limited measurements of residential radon exposure (Darby et al. 2006b), only slightly lower than the extrapolation of the risk derived from studies of miners. Similarly, the excess risk ratio per 100 Bq/m^3 radon in the North American pooled residential study increased from 10% to 18% when the analysis was restricted to individuals with measurements for at least 20 of the 25 years of radon exposure when spatial mobility was considered (Krewski et al. 2006). As noted by Field and Withers (2012), any remaining non-differential radon exposure measurement error would tend to bias the observed association toward the null and it is quite possible that more precise radon measurement in residential studies (such as based on annual radon levels) would result in a higher estimate for excess relative risk.

Structural uncertainty considers whether the chosen model structure adequately captures the exposures relevant to the health effect being evaluated, for the population being modelled. Structural uncertainty is examined in the study of global burden of lung cancer mortality associated with radon by comparing the results for Canada of a life-table analysis, which incorporates all-cause mortality rates and survival, to the results from the attributable fraction approach based on reported lung cancer mortality used in the main analysis. The results for Canada from both methods are comparable, when using the BEIR VI exposure-age-concentration model for excess relative risk, with a population attributable risk of 16.3% (95% CI: 2.6, 32.4) from the attributable fraction approach and a population attributable risk of 14.7% (95% CI: 2.0, 30.0) from the lifetable analysis. Structural uncertainty is examined in the health economic evaluation used to determine the incremental cost utility ratio of practical interventions to reduce radon exposure in Canada that are implemented gradually across the housing stock over a 100 year time horizon. The incremental cost effectiveness ratio results determined using a Markov cohort model are comparable to those determined from a discrete event simulation model for Canada (shown in Table 29), therefore it appears that minimal structural uncertainty is associated with the choice of model used in the cost-utility analysis. The discounted ICER for mitigation of existing housing above an active mitigation threshold of 200 Bq/m^3 is 62,451 $/QALY at the current rates using the cohort model and 66,421 $/QALY using the discrete event simulation model, and under a tax credit incentive is 48,021 $/QALY for the cohort model and 42,788 $/QALY using the discrete event simulation model. At an active mitigation threshold of 100 Bq/m^3, the discounted ICER is 58,866 $/QALY using a cohort model and 59,556 $/QALY using a discrete event simulation model at the current rates of radon testing and mitigation, and 51,866 $/QALY using the cohort model and 47,353 $/QALY using the discrete event simulation at the increased rates under the tax credit incentive.

7.5 Limitations

The most significant limitation in the estimation of the global population attributable risk of lung cancer mortality from residential radon exposure is uncertainty in the evaluation of national residential radon distributions. A representative national radon survey is required to assess the burden of lung cancer associated with residential radon and many countries lack a representative national survey. In other countries, radon measurement in regions known to have high residential radon has dominated radon surveys. Extrapolation of these measurements to the national scale can lead to overestimation of the burden from radon.

In the evaluation of the burden from residential radon in Canada, and gains from reducing that burden, uncertainty around the true radon exposure from the measurement of residential radon is a less important limitation. A single representative national radon survey has been recently conducted, based on 3 month long winter measurement using alpha track detectors. An adjustment was made for uncertainty from annual variation estimated from the difference in measured radon exposures for the 33 census metropolitan areas between the survey of census metropolitan areas and the national radon survey. A study evaluating annual variation from repeated measurements in housing and a follow-up national survey for Canada would be helpful to reduce the uncertainty in residential radon exposures, while updating the national survey would enable assessment of radon reductions following implementation of radon intervention policies.

A limitation of these analyses is that no differentiation is made between excess cases and etiologic cases of radon attributable lung cancer deaths prevented. The radon attributable fraction of lung cancer can be considered to include etiologic cases among smokers as well as excess cases. It is recognized that about 6 in 7 radon related lung cancer deaths are caused jointly by radon and active smoking and that only 1 in 7 are caused by radon alone (Gray et al. 2009). The greater number of deaths prevented and QALYs gained per smoker results from these etiologic cases in which radon is a causal factor. As a result, removing all radon exposures might delay until a later age rather than prevent these cases.

It has been recognized that if all the population attributable fractions from the various causes of lung cancer are added up, it will likely sum to more than one because only excess cases can be defined as the cases that would not occur if the exposure were removed (Greenland and Robins 1988). Many of the studies of excess relative risk of lung cancer from radon do include smoking as a confounder, but many do not include other possible confounders. For example, studies of outdoor particulate air pollution and lung cancer do not include residential radon as a confounder, and studies of residential radon and lung cancer do not include particulate air pollution as a confounder. For etiologic cases, many lung cancer causes may be contributing to individual cases identified in case-control studies of radon and lung cancer. It is expected that some overestimation of the population attributable fraction is possible for lung cancer attributable to residential radon.

The most significant limitation of the cost utility analyses of radon intervention scenarios that could reduce residential radon exposures in Canada is that they are limited to lung cancer mortality and do not include lung cancer morbidity. An improved estimate of the incremental cost effectiveness ratios for potential radon interventions to reduce residential radon exposures in the population would enable a more accurate comparison with lung cancer screening and treatment programs. This would be even more important should expensive new chemotherapy drugs targeted at specific genetic mutations be approved in Canada. It was determined that a lung cancer screening program targeting people identified as being at high risk that has an incremental cost effectiveness ratio of 20,724 $/QALY might become cost-saving if these new targeted chemotherapy drugs were to be approved. A similar change in the cost effectiveness of residential radon interventions would be expected.

Uncertainty concerning the effectiveness of specific radon prevention and radon mitigation techniques installed in Canadian housing, including differences in the construction industry, radon legislation, and the climate across the country, is another important limitation. The estimate of the effectiveness of passive preventive radon measures installed in new housing at construction was derived from a field study of 423 houses conducted in south west England that compared the radon levels in houses that did have passive preventive measures installed at construction with those that had no radon control measures (Woolliscroft et al. 1994). The comparison was between different houses, which is a limitation, however it provides a reasonable estimate because it is not possible to test the counterfactual ideal of testing radon exposure in a single house build both with and without preventive measures installed at construction. Passive preventive measures must be installed correctly to yield the effectiveness estimated from the study above, and contractors and builders who are installing the radon preventive measures in housing may not have the knowledge and experience to achieve the effect estimated for this analysis. In Canada, there is a program to educate and certify building contractors who offer radon preventive/mitigation services, but it is possible that the effectiveness of the radon control measures that are currently being installed in Canadian housing is somewhat lower than is estimated in this analysis.

The performance of radon prevention and mitigation measures over time will vary, in addition to the effectiveness of the initial implementation due to characteristics of the housing unit in which it is installed. Monitoring radon levels by conducting follow up radon testing, replacement of fans for active depressurization systems, and inspection for ice build-up in the stacks during the winter are all required for continued effectiveness of an initial installation. Vigilance regarding maintenance of a radon mitigation system will vary among home owners, and subsequent owners who inherit a radon mitigation system when they purchase a house with a system already installed may be less motivated to maintain it than the original home owners. Lastly, the reduction in radon exposure in this model is assumed to be a percentage of the initial radon level but independent of the magnitude of the initial level. This assumption is conservative because it underestimates the greater reductions that result from higher initial levels while there is little effect from the slight overestimates in the reduction of lower initial levels.

The BEIR VI exposure-age-concentration model for excess relative risk of lung cancer mortality from radon was used in the analyses of the lung cancer burden associated with residential radon in Canada and the cost-utility analyses of practical interventions to reduce residential radon in Canada. The residential radon exposure is measured as a concentration in Bq/m^3, which is then converted into a cumulative dose in working level months per year for use in the BEIR VI exposure-age-concentration model. This conversion requires an estimate of the average time spent at home, and the standard assumption of 7000 hours per year spent at home (Tirmarche et al. 2010) was used in this thesis. A limitation of this assumption is that it represents all the time in a week not spent at work during a standard work week of 40 hours. Therefore, different radon exposures that occur either during the standard 40 hours at work or school are not accounted for, and neither are different radon exposures that occur during the commute from work to home or during social or leisure activities. For example, higher radon exposures might occur due to the increased breathing rate experienced while exercising in an indoor facility and lower radon exposures would be expected during the commute between work and home. More time is spent at home than anywhere else, so this assumption is not expected to be a major limitation but it does exclude radon exposures at work or school and does not include differing radon exposures from locations other than at home in the estimate of the cumulative radon exposure that an individual experiences over a lifetime.

Representing the gradual implementation of radon interventions scenarios for new and existing housing in the housing stock over a hundred year time horizon in a model requires simplification of a very complex situation. The estimation of the overall costs and QALYs resulting from reducing residential radon in the model requires the use of many approximations. The use of the 2012 population with replacement over the time horizon included the effect of estimated population growth over time but did not include the aging of the population. This is an important factor because the burden of lung cancer will increase with an aging population, and the incremental cost effectiveness ratio in this model is therefore expected to be conservative. Smoking is the most important cause of lung cancer and it is the most important confounder for radon and lung cancer. Simplification of smoking status into current, former and nonsmoker in the model does not currently allow the range in relative risk of lung cancer morality and overall mortality with intensity of smoking for current smokers to be modelled. A final simplification of this model was not to consider effects of residential mobility of the population. It was assumed that a household would be exposed to a constant level of residential radon until mitigation of housing occurred, after which the lower exposure would be applied. Residents were assumed never to move from a lower residential radon exposure to a higher one.

The housing model is based on rates averaged over the decade that spans the year 2012 for which the analysis is conducted. As for other parameters, the current situation was projected over the 100 year time horizon so that the model would be focused on the main outcome, the effect and cost of residential radon interventions. The number and growth rate for housing stock and new construction are modeled, with some of the new construction housing the growth in the population while some is assumed to contribute to the replacement of older housing stock. Until very recently, more residential construction investment has been made in new construction, but since mid-2016, more investment has been made in renovations and apartment building construction. This housing model will overestimate the renewal of the housing should this recent trend continue, and would therefore overestimate the contribution of passive preventive measures installed at construction to the reduction of radon exposures in the population overall. In addition, should the number of resident owners decrease and the number of renters increase, fewer houses would be expected to have radon mitigated. There is no requirement for landlords to reduce high radon levels detected in rental housing. Estimates of current construction costs for radon mitigation are used for the entire time horizon, which is conservative because these would be expected to continue to decrease with increasing uptake of radon mitigation.

Current residential radon exposures in Canada were associated with a mean of 3,277 (95% CI: 518, 6,521) lung cancer deaths annually, representing 4.4% of total cancer deaths, from the analysis reported in Chapter 2. The incremental cost-utility ratios estimated for practical interventions to reduce residential radon in Canada are based on data sources that have uncertainty associated with them, leading to the limitations to the analyses described above. The major sources of uncertainty can be reduced in the future after further research, and some of this research is already being conducted, but decisions about whether to invest in radon reduction in Canadian housing need not be delayed. The goal of health economic evaluation is to help decisions-makers reach informed choices when distributing limited resources by providing estimates of the costs and outcomes of alternate courses of action. Whether the decision is to adopt a new intervention or to maintain the status quo, it is a decision that must be taken at the current level of uncertainty. The cost effectiveness acceptability curve is a graphical representation of the probability that an intervention is cost effective compared to another over a range of cost effectiveness thresholds that is a useful way of characterizing the uncertainty associated with a decision. The preparation of a cost effectiveness acceptability curve is recommended in the next section, Future Work, subsection v) extending the probabilistic decision modelling.

An equitable distribution of the benefits from policies designed to introduce radon control measures in housing in Canada across the population would require rental housing in addition to housing owned by residents to be included. The legal argument for requiring high radon exposures in rental housing to be mitigated is stronger than for resident-owned housing, because there an obligation for landlords to provide a housing unit that is "fit for habitation and at the landlord's expense comply with health, safety, housing and maintenance standards" (Dunn and Cooper 2014). Efforts to increase radon testing and mitigation have, however, been focussed on home owners in Canada, and there are currently no requirements for landlords to test radon exposures in rental housing.

Ideally, the analyses would be improved and the limitations described above would be decreased if data was currently available for the effectiveness in Canadian housing of commercially installed radon control measures, if time series of radon measurements were available for more housing in Canada, if more Canadian data on lung cancer were available, and more data was available for the housing characteristics in the provinces and territories.

The most important data to improve the cost-utility analyses would be Canadian data for the effectiveness of commercially installed passive preventive measures in new housing, activation of the depressurization system in new housing where above threshold radon levels are measured, and retrofitting active depressurization systems in existing housing. The effectiveness of installing passive preventive radon measures in new housing would require the radon levels in housing with the preventive measures compared to radon levels in housing with no radon control measures, because it is the counterfactual ideal for one house under construction to both have and not have preventive radon measures. As long as a large sample size is obtained for such a field trial, it would be expected to yield representative results. The effectiveness of the activation of a depressurization system in new housing and a retrofit for an active depressurization system would require only a before and after radon measurement in each house identified as having above threshold radon levels. Again, ideally a large sample size would be obtained that would enable a probabilistic distribution to be specified for the effectiveness, to replace the point estimates used in the current analyses. Lastly, repeat measurements every 5 years would give ideal data for a probabilistic distribution describing how well an active depressurization system is maintained in a real population in Canada. Repeat radon testing in housing with an active depressurization system installed would also be ideal, to monitor how long the passive preventive radon measures remain effective, and if the effectiveness declines with time, at what rate that occurs.

It would be very helpful also if a series of repeated radon measurements taken in Canadian housing were available. The seasonal and annual variation in the radon exposures could then be estimated, and the uncertainty in the representative radon distributions for Canadian populations could be reduced. It would also be ideal if a second representative national radon survey (based on 3 month-long winter measurements using alpha track detectors) could be carried out within ten years, so that the effect of mandating passive radon preventive measures in new housing could be assessed for those provinces and territories. Any changes in a second representative radon survey when compared to the 2009-2011 national radon survey would complement data collected from potential field trials described above to assess the effectiveness of the radon intervention techniques in housing in Canada. A pilot study conducted in a high radon region such as Winnipeg could also provide useful data at lower cost than a second national radon survey.

The availability of Canadian data on lung cancer at the provincial and territorial level, including stage at diagnosis, progression, and treatments would be ideal. It would also improve the models if Canadian data was available describing the relative risk by age and sex for the risk of lung cancer of smokers relative to nonsmokers. Canadian estimates could then be used instead of the estimates based on US data that are currently used in the analyses. It would be very helpful if there was Canadian data on the variation in the joint effect of smoking and radon on the risk of lung cancer, which is known to range from super-multiplicative in light smokers to sub-additive in heavy smokers. If this data were available then the model could be improved by expanding the categories of smoking intensity used in to model.

It would improve the analysis to have data characterizing changes in the housing stock at the provincial and territorial level, including rates for housing stock growth, new housing starts and demolitions used in the housing model. Data describing the distribution of the age of housing at the provincial and territorial level would also improve the housing model used to represent the gradual introduction of the radon interventions.

7.6 Future Work

Future work to continue this research investigating the health economic analysis of practical interventions to reduce residential radon exposures in target populations would include i)extending the analysis to incorporate the effects of lung cancer morbidity on both health gains and costs, ii)exploring the effects of changes in the behavior of individuals in a population using the discrete event simulation model, iii)exploring the effects of changes over time for model parameters using the discrete event simulation model, iv)assessing the impact of new radon reduction technologies, and v)extending the probabilistic decision modelling.

i) Extending the analysis to include the effects of lung cancer morbidity on both health gains and costs

The health economic evaluation should be extended to incorporate the radon attributable lung cancer morbidity in addition to mortality in the estimate of incremental cost effectiveness ratio for practical radon mitigation scenarios to reduce residential radon exposures in Canada. It has been estimated that $17 million dollars in annual lung cancer treatment costs would be saved if homes with radon levels above 200 Bq/m^3 were mitigated, as recommended in the voluntary radon guideline (Dunn and Cooper 2014). Lung cancer morbidity has been included in the estimate of the cost-effectiveness of radon mitigation in the UK (Gray et al. 2009) and in Norway (Stigum et al. 2003), with the savings from reduced lung cancer treatment costs balanced by the average annual health care costs accrued by the people in whom lung cancer is prevented. Health protection interventions can be very cost-effective, while the costs of lung cancer treatment continue to rise rapidly. Improved estimates of the cost-effectiveness of residential radon mitigation that includes reduction of radon attributable lung cancer morbidity as well as mortality could more accurately provide policy options to complement lung cancer screening and treatment.

Five-year survival rates for lung cancer in Canada were estimated to be 17% between 2006-2008, and 19% for Ontario, reported by the Canadian Cancer Registry (Canadian Cancer Society et al. 2014). Lung cancer stage at diagnosis and survival curve for stage at diagnosis are reported. A life-table approach using Markov chain Monte Carlo simulation will involve five Markov states: healthy, stage A lung cancer, stage B lung cancer, stage C lung cancer, and dead. The three lung cancer stages correspond to local (A), regional (B) and disease distant metastases (C), as described by Villanti et al. (Villanti et al. 2013). Utility values for lung cancer stages were identified as follows: QALY weights: A – 0.823, B – 0.772, C – 0.573 in a meta-analysis by Sturza (Sturza 2010). Survival probabilities by smoking category for men and for women are available from Schoenbaum (Schoenbaum 1997).

Lung cancer is usually treated by chemotherapy and radiation for the more aggressive small cell lung cancer, and for non-small cell lung cancer, it is treated primarily by surgical resection and chemotherapy. The largest burdens are experienced during the treatment time following diagnosis, and costs include those for chemotherapy, radiotherapy, cancer-related surgery, other admissions to hospital and home care. Canadian data on lung cancer treatment costs in 2013 dollars during the first two years after diagnosis (Cressman et al. 2014) are derived using physician fees and clinical services based on the 2013 schedules from the Medical Service Plan in the province of British Columbia, Canadian wholesale drug prices were used for chemotherapy drugs, and hospitalization costs from Ontario data. The average cost in 2013 dollars for the first two years of lung cancer treatment was estimated to be $33,344 (95% CI: $31,533 - $34,935) for cases diagnosed at initial stages and to be $47,792 (95% CI: $43,254 - $52,200) for cases diagnosed at advanced stages. Although health care is under provincial jurisdiction in Canada, it is suggested that these averaged treatment costs be employed for each province/territory.

ii) Exploring the effects of changes in the behavior of individuals in a population using the discrete event simulation model

The discrete event simulation model being developed is a versatile research tool that offers the opportunity to investigate the effect of changes in the behavior of individuals in a population. It would be very interesting to model the effect of changes in individual smoking behavior, since most smokers try to quit many times before succeeding. Based on recent research estimating the relative risk of former smokers (Kenfield et al. 2008; Pesch et al. 2012), an exponential distribution would be appropriate to model the relative risks of lung cancer and overall mortality of current smokers compared to nonsmokers, which drop quite quickly with time since quitting and approximately equals the risks for nonsmokers after 20 years. In the cohort model, the proportion of former smokers in the population was modelled according to time since quitting over a 20 year period, but the ability to model individual behaviour in the discrete event simulation model makes it much better suited for exploring the interaction between smoking and radon exposures. The interaction of smoking with radiation on the incidence of lung cancer was investigated using the atomic bomb survivors in the Life Span Study and the joint effect was reported to appear to be super-multiplicative for light/moderate smokers but additive or sub-additive for heavier smokers (Furukawa et al. 2010). The intensity of smoking could be added to the discrete event simulation model for current smokers if this line of research was pursued further. It would also be interesting to model the effect of smoking cessation programs on lung cancer incidence, and to compare current smoking cessation programs with radon intervention scenarios to reduce radon attributed lung cancer incidence. In a study of home owners requesting radon test kits in Kentucky, US, current smoking and prior knowledge that the risk of lung cancer from the combination of radon and smoking is higher than from smoking alone were significant factors for the likelihood of planning to test residential radon (Rinker et al. 2014). The extension of the model to include the joint effect of smoking and radon for radon interventions might demonstrate benefit to light/moderate smokers in addition to heavier smokers as a relevant subgroup to target within a focussed radon awareness campaign.

iii) Exploring the effects of changes over time for model parameters using the discrete event simulation model

The discrete event simulation model also offers the opportunity to investigate the effect of changes of the time horizon for model parameters, such as changes in the representative national radon distribution as radon prevention and mitigation become more common, demographic changes, changes in the housing stock, and changes in costs of radon prevention and mitigation. The sensitivity of the incremental cost effectiveness ratio to changes in the balance of new and existing housing will be investigated in the discrete event simulation model. Updated estimates of the age- and sex-specific health related quality of life have recently been derived using the reported Health Utilities Index Mark 3 from the 2013-2014 CCHS for Canada (Guertin et al. 2018) and these updated utility values would be incorporated into the analysis.

The demographic situation is changing in Canada because the population is aging, which translates to an increase in the concentration of people at older ages (Shumanty 2018). This is significant when evaluating radon attributed lung cancer because lung cancer incidence and mortality occurs predominantly at older ages, mostly over age 65 for men and women in Canada. This aging trend of the population in Canada is expected to continue into the near future as the baby-boom cohort ages. It will be important to incorporate the changing demographic situation in Canada in addition to the overall growth of the population over time into the health economic evaluation so rational policies can be developed that optimize the prevention of radon attributable lung cancer and establish a balance between lung cancer prevention and treatment in our health care system.

Socio-economic factors and tax policies are very important to consider when modelling changes to the housing stock over time. Tax policies have been instrumental in Canada to encourage home ownership since the 1950s post war boom, and while many incentives are still available to home owners from federal and provincial governments, the rental market has largely been left to private market forces since the federal government withdrew funding for affordable rental development in the 1990s (Coté and Tam 2013). Higher income is usually associated with higher spending, but households in the lowest income quintile in Canada spend about 35% of their consumption of goods and services on shelter while those in the highest income quintile spend about 27% on shelter (Statistics Canada 2017). The generational income gap also has an impact on home ownership; the majority of resident owners in Canada are over 55 years of age and fewer than 10% are under 35 years of age (Statistics Canada 2018a). It will become increasingly important to consider reducing the residential radon exposures of renters in the future, as the trends of the widening income gap and the decreasing proportion of home ownership in Canada are expected to continue unless significant policy changes are made at provincial and federal levels.

iv) Assessing the impact of new radon reduction technologies

New radon prevention and mitigation technologies will continue to be developed as the radon remediation becomes more common. In Canada, Health Canada's Radiation Protection Bureau and the National Research Council are both involved in evaluating the effectiveness and reliability of new radon technologies. Full passive stacks installed at construction constitute an intermediate option between the current requirements for preventive measures in the NBC and an active depressurization system. Testing is underway in BC and in Ottawa to measure the reduction in residential radon exposure achieved from full passive stacks, which are expected to be most effective for housing with radon levels between 150 and 400 Bq/m^3. The range of radon prevention and mitigation options modelled in the health economic analysis could be extended by the addition of a full passive stack once data on its effectiveness and costs have been characterized in Canada. A reduction in the costs of radon measurement could result from the use of a continuous radon meter, once the accuracy of this technology is equivalent to the gold standard of radon measurement, the 3 month long winter measurement using an alpha track detector. Radon measurement is required for ongoing screening of the housing stock to identify those with above mitigation threshold levels and for monitoring housing with passive or active radon depressurization systems installed. Residential radon measurement constitutes an important cost when evaluating the incremental cost effectiveness ratio for radon interventions; one of the reasons that the installation of passive preventive measures at construction is so cost effective is that no screening or monitoring costs are incurred.

V) Probabilistic decision modelling

Probabilistic decision modelling would be extended by presenting the parameter uncertainty encompassed by the cost utility model in a way that is helpful to decision makers. The uncertainty surrounding the incremental cost effectiveness ratios of radon intervention scenarios would first be estimated for a range of cost effectiveness thresholds by constructing a cost effectiveness acceptability curve (CEAC). For a range of values of willingness to pay for an additional QALY, further simulation would yield the data required to enable the construction of a cost effectiveness acceptability curve for each intervention scenario showing the probability that it would be cost effective compared to the specific comparator (for that step in the sequential analysis). The cost effectiveness acceptability curve would help to determine the robustness of a decision to adopt an intervention on the basis of existing evidence.

It might also be helpful to assess whether it is worthwhile to invest in further research to reduce uncertainty surrounding the decision by conducting a formal value of information (VOI) analysis. The challenge of using a value of information analysis for environmental health risk management has been reported to derive mostly from defining continuous probability distributions as inputs in models approximating complex problems (Yokota and Thompson 2004). Future radon surveys will help to characterize the uncertainty associated with the residential radon distribution. Current research being conducted at the National Research Council and in British Columbia will help establish distributions describing the effectiveness of the radon prevention and mitigation techniques used in the Canadian climate. The discrete event simulation model can help to assess the sensitivity of the incremental cost effectiveness ratio to the transition from renovations to existing housing dominating new construction as the housing stock changes to accommodate the growing population. Once distributions can be defined for most parameters in the model, the underlying uncertainty within the economic evaluation of the incremental cost effectiveness ratio can be assessed from a value of information analysis. Whether investing in further research may be worth the cost can be assessed by calculating the associated opportunity loss. For a range of values of willingness to pay for an additional QALY, the reduction in opportunity loss associated with obtaining perfect information for all parameter values can be estimated from the expected value of perfect information (EVPI) and the opportunity loss associated with each parameter can be estimated from the partial EVPIs (EVPPIs). However, multiple intervention scenarios to reduce residential radon have been evaluated and all possible strategies would need to be included in the analysis, even the ones excluded due to dominance or extended dominance, in order to estimate the value of information.

7.7 Conclusions

Trachea, bronchus and lung cancer were reported to represent 19% of all cancer deaths and was ranked as the fifth leading cause of death worldwide for all ages in 2010 by the World Health Organisation. The global burden from lung cancer mortality is increasing, with the number of lung cancer deaths rising by 57% between 1990 and 2013. Lung cancer is the cancer with the highest mortality rate in Canada, having a 5 year survival rate of only 15%. Lung cancer was ranked as the second leading cause of years of life lost in 2010 in Canada, representing 8.8% of the total years of life lost in Canada. The number of years of life lost to lung cancer have increased by 21% since 1990 (IHME 2013). The low survival rate for lung cancer makes the evaluation of preventive health interventions compelling.

Radon is the second most important cause of lung cancer and evaluating radon prevention and mitigation technologies is worthwhile because they are very effective at reducing residential exposures in housing. In Canada, installing preventive measures at construction to impede the ingress of radon into new housing costs very little, and the cost of active mitigation of radon in existing housing is decreasing steadily. Rational health policy decisions for the allocation of limited resources can be informed by a cost utility analysis of potential radon intervention scenarios to reduce residential radon and the associated lung cancer burden in Canada. The annual cost for lung cancer treatment in Canada was estimated to be 7.5 billion dollars in 2012 (de Oliveira et al. 2018). It is valuable to evaluate residential radon remediation as a health intervention instead of a purely environmental intervention because it is the health care system that is responsible for treating radon attributable lung cancer cases.

The global burden of lung cancer mortality attributable to radon in 2012 was estimated from the 66 countries for which a representative national radon survey was available, using five different models for excess relative risk of lung cancer from radon, three from cohorts of miners and two from pooled residential studies. The estimates of the global median population attributable risk were consistent, ranging from 16.5% to 13.6% for the models based on miners, and the mean estimates of population attributable risk for Canada ranged from 16.3% to 14.6% for the models based on miners. The population attributable risk estimates using excess relative risk models derived from residential studies were a little lower; these excess relative risk models were subject to much greater radon measurement error in the residential exposures and may underestimate the risk. The modifiable burden of disease for the 2012 Canadian population was assessed as the gain in quality-adjusted life years (QALYs) from two interventions in new construction (50% and 85% reductions in radon exposures) using a period life-table analysis based on 5 year periods. At a discount rate of 1.5%, a reduction of residential radon by 50% was associated with a period gain of 15,445 QALYs and a reduction of 85% resulted in a period gain of 26,336 QALYs.

It is very cost effective to install radon preventive measures in new construction compared to no radon control in all regions across Canada, and it is recommended that this be mandated in the few provinces that have yet to adopt this part of the National Building Code of Canada. Sequential analyses were conducted for the incremental cost utility ratios for sixteen practical radon intervention scenarios, to reduce residential radon exposures in Canada, each province/territory and 17 census metropolitan areas. The incremental cost effectiveness ratios were estimated using a cohort Markov model based on a period-life table analysis over a lifetime horizon at a discount rate of 1.5%. The most cost effective radon intervention scenario compared to the baseline passive preventive measures in new housing is the combination of the activation of preventive measures in new housing with the mitigation of existing housing at current testing and mitigation rates. This radon intervention scenario is recommended for Canada at cost effectiveness thresholds between 51,889 and 92,072 $/QALY at an active radon mitigation threshold of 100 Bq/m^3. It is recommended at cost effectiveness thresholds between 15,801 and 36,547 $/QALY for the Yukon and between 27,558 and 85,965 $/QALY for Manitoba at a mitigation threshold of 100 Bq/m^3. Greater investment in radon reduction is recommended where a range of intervention scenarios are cost effective, either for a lower radon mitigation threshold or using a tax credit incentive. These regional populations include Nova Scotia, New Brunswick, Quebec, Manitoba, Saskatchewan, the Yukon, the Northwest Territories, St. John’s, Halifax, St. John, Quebec City, Sherbrooke, Montreal, Ottawa-Gatineau, Kingston, Windsor, Winnipeg, Saskatoon, Regina, Calgary, and Kelowna. It is not cost effective to install active depressurization systems in all new housing. The preliminary discrete event simulation of incremental cost effectiveness ratios for mitigation of existing housing are consistent with the Markov model results and show that the incremental cost effectiveness ratio estimates are sensitive to changes in the housing stock.

Residential radon interventions should be implemented in Canada to reduce exposures to this very modifiable cause of lung cancer and to help reduce the increasing lung cancer burden in an ageing Canadian population. A sequence of interventions is recommended at increasing cost effectiveness thresholds in the Canadian context, allowing flexibility under budget constraints. Three types of model uncertainty associated with the health economic model to estimate ICERS were investigated, parameter uncertainty, ERR model uncertainty, and structural uncertainty. The next step to determine the robustness of the decisions based on these estimated ICERs would be to conduct a formal evaluation of the probability the intervention is cost effective for specific cost effectiveness thresholds using a cost effectiveness acceptability curve. It is recommended that the cost utility analysis of the prevention of radon attributed lung cancer through implementation of residential radon interventions be extended to include lung cancer morbidity as well as mortality to help decision makers to balance lung cancer prevention and lung cancer treatment programs in the health care system. Ongoing updating of the national radon survey by the National Radon Program will be required, probably every 20 years or so, to measure the population effect of building code changes, education and incentives on residential radon levels.

7.8 References

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Appendix A – Supplementary Material for Chapter 2

Table S1 – References for reported national residential radon exposures

Country	**RnArithMn**[a] (Bq/m^3)	**RnGeoMn**[b] (Bq/m^3)	**RnGeoSD**[c]	**Reference**
Albania	101			(Tushe et al. 2016)
Algeria	30			(Cherouati and Djeffal 1988)
Argentina	37			(Canoba et al. 2002)
Armenia	104		1.3	(UNSCEAR 2000)
Australia	11.6	8.7	2.1	(Langroo et al. 1990)
Austria	99	61		(Friedmann 2005)
Belarus	31.8			(UNSCEAR 2006)
Belgium	48	38	2	(UNSCEAR 2006)
Brazil	41			(Veiga et al. 2007)
Bulgaria		80	2.1	(Ivanova et al. 2013)
Canada		41.9	2.8	(Chen et al. 2012)
Chile	25		1.8	(Stuardo 1996)
China	43.8	34.4		(UNSCEAR 2006)
Croatia	68	50	2.3	(Radolić et al. 2006)
Cuba	7.7	5.2	3.3	(UNSCEAR 2006)
Cyprus	7	7	2.6	(UNSCEAR 2006)
Czech Republic	118	94.4	1.84	(UNSCEAR 2006)
Denmark	59	39	2.2	(UNSCEAR 2006)
Ecuador	94.3			(Canoba et al. 2002)
Egypt	9			(UNSCEAR 2006)
Estonia	60			(Pahapill et al. 2003)
Finland	120	84	2.1	(UNSCEAR 2006)
France	63		2.0	(Billon et al. 2005)
Germany	49	37	2.2	(Haucke 2010)
Greece	55	44	2.4	(Nikolopoulos et al. 2005)
Hungary		62	2.07	(Hámori et al. 2006)
Iceland	10			(UNSCEAR 2006)
India	57	42	2.2	(UNSCEAR 2006)
Indonesia	35.1	35.1	1.2	(UNSCEAR 2006)
Iran	82			(UNSCEAR 2006)
Ireland	77	51	2.4	(Dowdall et al. 2017)
Israel	31			(Epstein et al. 2014)
Italy	70	52	2.1	(Bochicchio et al. 1999)
Japan	13.7	10.4	2	(Suzuki et al. 2010)
Kazakstan	15			(UNSCEAR 2006)

Country	**RnArithMn[a]** (Bq/m^3)	**RnGeoMn[b]** (Bq/m^3)	**RnGeoSD[c]**	**Reference**
Kuwait	32.8	26.5	1.9	(Al-Azmi et al. 2008)
Lithuania	55	36.5		(UNSCEAR 2006)
Luxembourg	110	70	2	(UNSCEAR 2006)
Malaysia	14			(UNSCEAR 2006)
Mexico	84	82.1	1.25	(Espinosa and Gammage 2011)
Montenegro	105	49.6	3.2	(Vukotic et al. 2008)
Netherlands	15.6	12.2		(Smetsers et al. 2016)
New Zealand	21.5	19.5		(UNSCEAR 2006)
Norway	74.5	38	3.19	(Stigum et al. 2003)
Pakistan	70			(Faheem et al. 2008)
Paraguay	28			(UNSCEAR 2006)
Peru	32.29			(Canoba et al. 2002)
Philippines	23	22	1.13	(UNSCEAR 2006)
Poland	165	133	1.91	(Kozak et al. 2011; Przylibski 2015)
Portugal	62	45	2.2	(Faisca et al. 1992)
Republic of Korea	62	49	2	(Kim et al. 2011)
Romania	126	84	2.5	(Cosma et al. 2013)
Russian Federation	48			(Yarmoshenko et al. 2015)
Saudi Arabia	22			(Abu-Jarad et al. 2003)
Slovakia		48	3.3	(Vicanova et al. 1998)
Slovenia	87	60	2.2	(Križman et al. 1996)
Spain	80.3	52.9	2.5	(Sainz-Fernandez et al. 2014)
Sweden	90			(Axelsson et al. 2015)
Switzerland	71	51		(Menzler et al. 2008)
Syrian Arab Republic	44			(Othman et al. 1996)
Thailand	23	16	1.2	(UNSCEAR 2006)
Tunisia	45.5			(El May et al. 2008)
Turkey	81	57	2.3	(Celebi et al. 2015)
UK	20	14	3.2	(UNSCEAR 2006)
USA	46	25	3.1	(Marcinowski et al. 1994)
Venezuela	52.5			(Canoba et al. 2002)

Notes: a) RnArithMn - arithmetic mean of national radon distribution, b) RnGeoMn - geometric mean of national radon distribution,
c) RnGeoSD - geometric standard deviation of national radon distribution.

The following 22 countries had radon GSD imputed because they only reported an arithmetic mean residential radon exposure (see Table S1): Albania, Algeria, Argentina, Belarus, Brazil, Ecuador, Egypt, Estonia, Iceland, Iran, Israel, Kazakhstan, Malaysia, Pakistan, Paraguay, Peru, Russian Federation, Saudi Arabia, Sweden, Syria, Tunisia, Venezuela.

Table S2 – National male and female adult smoking prevalence

Country	Male Smoking Prevalence (%) Mean ± SD	Female Smoking Prevalence (%) Mean ± SD
Albania	52 ± 6.3	8.2 ± 1.3
Algeria	28 ± 6.1	2.0 ± 0.2
Argentina	32 ± 3.1	21 ± 2.1
Armenia	55 ± 5.1	1.7 ± 0.2
Australia	18 ± 1.8	15 ± 1.4
Austria	37 ± 5.8	36 ± 6.2
Belarus	49 ± 5.1	11 ± 1.2
Belgium	28 ± 4.9	21 ± 4.2
Brazil	21 ± 2.4	12 ± 1.5
Bulgaria	45 ± 5.1	30 ± 4.0
Canada	20 ± 1.7	14 ± 1.3
Chile	42 ± 6.1	37 ± 5.1
China	49 ± 5.0	2.0 ± 0.2
Croatia	39 ± 5.1	32 ± 4.0
Cuba	53 ± 15.4	20 ± 6.2
Cyprus	41 ± 6.5	18 ± 4.0
Czech Republic	38 ± 4.0	29 ± 3.1
Denmark	21 ± 2.3	19 ± 2.1
Ecuador	15 ± 3.2	3.6 ± 0.9
Egypt	46 ± 5.5	0.4 ± 0.1
Estonia	44 ± 4.4	25 ± 2.7
Finland	25 ± 2.3	20 ± 1.9
France	31 ± 4.4	26 ± 3.6
Germany	34 ± 3.4	29 ± 2.7
Greece	54 ± 8.3	34 ± 7.1
Hungary	35 ± 4.1	27 ± 3.4
Iceland	19 ± 3.3	17 ± 2.5
India	23 ± 2.6	2.4 ± 0.3
Indonesia	72 ± 8.1	4.0 ± 0.4
Iran	23 ± 2.8	1.1 ± 0.2
Ireland	24 ± 3.2	24 ± 3.2
Israel	42 ± 7.0	20 ± 3.4
Italy	29 ± 2.4	20 ± 1.7
Japan	36 ± 3.9	11 ± 1.3
Kazakstan	46 ± 5.7	9.7 ± 1.4

Country	Male Smoking Prevalence (%) Mean ± SD	Female Smoking Prevalence (%) Mean ± SD
Kuwait	35 ± 4.1	4.0 ± 0.8
Lithuania	41 ± 5.0	22 ± 2.7
Luxembourg	27 ± 3.5	22 ± 3.1
Malaysia	45 ± 7.2	1.6 ± 0.3
Mexico	23 ± 2.2	7.6 ± 0.8
Montenegro	42 ± 5.3	26 ± 3.4
Netherlands	28 ± 2.8	25 ± 2.4
New Zealand	21 ± 2.1	19 ± 1.9
Norway	26 ± 2.2	25 ± 2.3
Pakistan	41 ± 5.7	3.6 ± 0.6
Paraguay	31 ± 5.1	9.0 ± 1.6
Peru	21 ± 0.6	6.5 ± 0.8
Philippines	46 ± 4.3	9.2 ± 1.0
Poland	35 ± 3.7	26 ± 2.8
Portugal	32 ± 4.2	14 ± 2.5
Rep. of Korea	52 ± 8.5	4.4 ± 1.0
Romania	40 ± 4.3	23 ± 2.5
Russian Fed.	60 ± 5.9	23 ± 2.5
Saudi Arabia	26 ± 3.5	3.0 ± 0.8
Slovakia	41 ± 8.0	18 ± 4.3
Slovenia	24 ± 2.9	19 ± 2.3
Spain	34 ± 3.5	28 ± 2.9
Sweden	22 ± 2.0	23 ± 2.0
Switzerland	28 ± 2.6	21 ± 1.8
Syria	48 ± 6.9	18 ± 2.6
Thailand	42 ± 3.6	2.4 ± 0.2
Tunisia	52 ± 6.1	11 ± 0.2
Turkey	43 ± 4.1	14 ± 1.4
UK	22 ± 2.4	20 ± 2.4
USA	21 ± 1.9	16 ± 1.5
Venezuela	28 ± 4.7	16 ± 2.5

Note: The source of this data was the WHO Global Health Observatory for 2012

The following 9 countries had imputed or combined averaged/imputed adult smoking prevalence and upper and lower confidence limits: Algeria, Cyprus, Kuwait, Montenegro, New Zealand, Peru, Syria, Tunisia, Venezuela

Table S3 - Radon population attributable risk (PAR) of lung cancer mortality, estimated from extending the pooled residential studies to model lifetime exposure

Country	Radon[a] GM (GSD) (Bq/m^3)	PAR (%) Krewski[b] Mean (95% CI)	PAR (%) Darby[c] Mean (95% CI)
median	38	**10.4**	**8.4**
Albania	75 (2.2)	18.0 (0, 33.7)	14.3 (3.2, 23.5)
Algeria	22 (2.2)	6.4 (0, 13.1)	4.8 (1.0, 8.3)
Argentina	27 (2.2)	7.7 (0, 15.6)	5.8 (1.2, 10.1)
Armenia	101 (1.3)	22.5 (0, 40.7)	18.2 (4.3, 29.3)
Australia	8.7 (2.1)	2.6 (0, 5.6)	1.9 (0.4, 3.5)
Austria	61 (2.7)	15.3 (0, 29.3)	12.0 (2.6, 20.0)
Belarus	23 (2.2)	6.7 (0, 13.8)	5.0 (1.0, 8.8)
Belgium	38 (2.0)	10.3 (0, 20.6)	7.9 (1.7, 13.5)
Brazil	30 (2.2)	8.4 (0, 17.1)	6.4 (1.3, 11.1)
Bulgaria	80 (2.1)	18.9 (0, 35.2)	15.1 (3.4, 24.7)
Canada	42 (2.8)	11.2 (0, 22.2)	8.6 (1.8, 14.7)
Chile	21 (1.8)	6.1 (0, 12.5)	4.5 (0.9, 8.0)
China	34 (2.0)	9.5 (0, 19.1)	7.2 (1.5, 12.4)
Croatia	50 (2.3)	13.0 (0, 25.4)	10.1 (2.2, 17.0)
Cuba	5.2 (3.3)	1.6 (0, 3.4)	1.2 (0.2, 2.1)
Cyprus	7 (2.6)	2.1 (0, 4.6)	1.6 (0.3, 2.8)
Czech Republic	94 (1.8)	21.4 (0, 39.0)	17.3 (4.0, 27.9)
Denmark	39 (2.2)	10.5 (0, 20.9)	8.1 (1.7, 13.8)
Ecuador	70 (2.2)	17.1 (0, 32.3)	13.5 (3.0, 22.4)
Egypt	6.6 (2.2)	2.0 (0, 4.3)	1.5 (0.3, 2.6)
Estonia	44 (2.2)	11.8 (0, 23.2)	9.1 (1.9, 15.4)
Finland	84 (2.1)	19.6 (0, 36.3)	15.7 (3.6, 25.6)
France	50 (2.0)	13.0 (0, 25.3)	10.0 (2.2, 17.0)
Germany	37 (2.2)	10.0 (0, 20.1)	7.7 (1.6, 13.2)
Greece	44 (2.4)	11.7 (0, 23.1)	9.0 (1.9, 15.3)
Hungary	62 (2.1)	15.5 (0, 29.7)	12.2 (2.7, 20.3)
Iceland	7.3 (2.2)	2.2 (0, 4.8)	1.6 (0.3, 2.9)
India	42 (2.2)	11.2 (0, 22.3)	8.6 (1.8, 14.7)
Indonesia	35 (1.2)	9.6 (0, 19.3)	7.3 (1.5, 12.6)
Iran	61 (2.2)	15.3 (0, 29.4)	12.0 (2.6, 20.1)
Ireland	51 (2.4)	13.2 (0, 25.7)	10.3 (2.2, 17.3)
Israel	23 (2.2)	6.5 (0, 13.5)	4.9 (1.0, 8.6)
Italy	52 (2.1)	13.5 (0, 26.2)	10.4 (2.3, 17.6)
Japan	10 (2.0)	3.1 (0, 6.6)	2.3 (0.5, 4.1)

Country	Radon[a] GM (GSD) (Bq/m^3)	PAR (%) Krewski[b] Mean (95% CI)	PAR (%) Darby[c] Mean (95% CI)
Kazakstan	11 (2.2)	3.3 (0, 7.0)	2.4 (0.5, 4.3)
Kuwait	27 (1.9)	7.5 (0, 15.4)	5.7 (1.2, 9.9)
Lithuania	37 (2.5)	9.9 (0, 19.9)	7.6 (1.6, 13.0)
Luxembourg	70 (2.0)	17.1 (0, 32.3)	13.5 (3.0, 22.4)
Malaysia	10 (2.2)	3.1 (0, 6.5)	2.3 (0.5, 4.0)
Mexico	82 (1.3)	19.3 (0, 35.8)	15.4 (3.5, 25.2)
Montenegro	50 (3.2)	13.0 (0, 25.3)	10.0 (2.2, 17.0)
Netherlands	12 (2.0)	3.6 (0, 7.7)	2.7 (0.5, 4.8)
New Zealand	20 (1.6)	5.6 (0, 11.7)	4.2 (0.9, 7.4)
Norway	38 (3.2)	10.3 (0, 20.5)	7.9 (1.7, 13.5)
Pakistan	52 (2.2)	13.4 (0, 26.0)	10.4 (2.2, 17.5)
Paraguay	21 (2.2)	5.9 (0, 12.3)	4.5 (0.9, 7.8)
Peru	24 (2.2)	6.8 (0, 13.9)	5.1 (1.0, 8.9)
Philippines	22 (1.1)	6.3 (0, 13.0)	4.7 (1.0, 8.3)
Poland	133 (1.9)	27.3 (0, 47.5)	22.6 (5.6, 35.4)
Portugal	45 (2.2)	11.9 (0, 23.5)	9.2 (2.0, 15.6)
Rep. of Korea	49 (2.0)	12.8 (0, 25.0)	9.9 (2.1, 16.7)
Romania	84 (2.5)	19.7 (0, 36.4)	15.7 (3.6, 25.7)
Russian Fed.	35 (2.2)	9.7 (0, 19.5)	7.4 (1.6, 12.7)
Saudi Arabia	16 (2.2)	4.7 (0, 9.9)	3.5 (0.7, 6.2)
Slovakia	48 (3.3)	12.6 (0, 24.6)	9.7 (2.1, 16.5)
Slovenia	60 (2.2)	15.1 (0, 29.0)	11.8 (2.6, 19.8)
Spain	53 (2.5)	13.7 (0, 26.5)	10.6 (2.3, 17.9)
Sweden	67 (2.2)	16.4 (0, 31.2)	13.0 (2.9, 21.5)
Switzerland	51 (2.3)	13.2 (0, 25.7)	10.3 (2.2, 17.3)
Syria	33 (2.2)	9.0 (0, 18.1)	6.8 (1.4, 11.8)
Thailand	16 (1.2)	4.7 (0, 9.8)	3.5 (0.7, 6.2)
Tunisia	34 (2.2)	9.3 (0, 18.7)	7.1 (1.5, 12.2)
Turkey	57 (2.3)	14.5 (0, 28.0)	11.3 (2.5, 19.0)
UK	14 (3.2)	4.1 (0, 8.7)	3.1 (0.6, 5.4)
USA	25 (3.1)	7.1 (0, 14.5)	5.4 (1.1, 9.3)
Venezuela	39 (2.2)	10.5 (0, 20.9)	8.0 (1.7, 13.7)

Notes: a) The sources of the national radon geometric means (GM) and geometric standard deviations (GSD) are described in Table S1; b) the mean and 95% confidence intervals of the population attributable risk (PAR) of lung cancer mortality from radon, converted to percentage, estimated by extending the pooled North American residential radon studies of excess risk ratio after restricting the analysis to individuals having measurements for at least 20 of the 25 years of radon exposure (Krewski et al. 2006); c)the mean and 95% confidence intervals of the population attributable risk (PAR) of lung cancer mortality from radon, converted to percentage, estimated by extending the pooled European residential radon studies of excess risk ratio after adjusting the limited measurements of residential radon for random uncertainties (Darby et al. 2006).

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Appendix B - National Building Code 2010, Radon Protection Provisions

National Building Code 2010, Radon Protection Provisions (Appendix 2, (Dunn and Cooper 2014)**)**

Radon Protective Provisions in the NBC, 2010

Radon protection provisions appear in Parts 5, 6 and 9 of the NBC, 2010. Part 5 addresses soil gas control, sets targets for the control of air leakage, and details air barrier system requirements to minimize the ingress of airborne radon from the ground with an aim to maintain the indoor radon concentration at an acceptable level. Part 6 addresses Good Engineering Practice. Part 9 is where the majority of radon protection provisions appear, and include provisions which address the control of the ingress of soil gases, and requirements for air and soil gas barriers (Sections 9.13, 9.18 and 9.25).

Part 5 (Environmental Separation)

Part 5 addresses soil gas control, sets targets for the control of air leakage, and details air barrier system requirements to minimize the ingress of airborne radon from the ground with an aim to maintain the indoor radon concentration at an acceptable level.

Article 5.4.1.1, requires that air leakage is controlled, or venting to the exterior permitted,[2] so as to:

[2] National Research Council of Canada: Canadian Commission on Building and Fire Codes, "National Building Code of Canada 2010," 13th ed., Second Printing (including revisions and errata released Dec. 21 2012), ISBN: 0-660-19975-7. Note this section applies " [w]here a *building* component or assembly separates interior *conditioned space* from exterior space, interior space from the ground, or environmentally dissimilar interior spaces"

[3] *Ibid* at Section 5.4, Subsection 5.4.1, Article 5.4.1.1, pp. 5-5.

[4] *Ibid* at Volume 2, A-5.4.1.1, pp. A-59 – A-60.

a) provide acceptable conditions for the *building* occupants,

b) maintain appropriate conditions for the intended use of the *building,*

…

e) minimize the ingress of airborne radon from the ground with an aim to controlling the indoor radon concentration to an acceptable level, and

f) not compromise the operation of *building* services.

Sentences 5.4.1.1 (2) and (3) requires the installation of an air barrier to provide the principal resistance to air leakage except where uncontrolled air leakage will not adversely affect any of

(a) the health of safety of *building* users,

(b) the intended use of the *building,* or

(c) the operation of *building* services. [3]

The Appendix to Part 5 (Article 5.4.1.1) notes that an air barrier system can reduce the likelihood of infiltration of dust and other pollutants which can lead to serious health or safety hazards. This section requires the installation of an air barrier system in components and assemblies in contact with the ground to control the ingress of radon. The Appendix references the new Health Canada guideline of 200 Bq/m³ for indoor radon concentration, stating that "[m]easures may be necessary to reduce the radon concentration to a level below the Health Canada guideline." [4] Part 5, Article 5.4.1.2, details the requirements for materials used to resist air leakage; specifies the air leakage limit and exemptions to the limit.[5] It also sets out that air barrier systems must be continuous,[6] and sets compliance standards with which the structural design of air barriers systems subject to air pressure loads must conform.[7] The Appendix to Part 5 (section 5.4.1.2 (1) and (2)) details materials and system requirements; notes the circumstances in which it may be acceptable to have air leakage characteristics in exceedance of the maximum provided in the Subsection 5.4.1.2; provides recommended maximum air leakage rates; and recommendations with respect to testing of air barrier airtightness. [8]

[5] *Ibid* at Part 5, Section 5.4, Sentences 5.4.1.2 (1) and (2).
[6] *Ibid*. Under Sentence 5.4.1.2 (3) continuity is required:
a) across construction, control and expansion joints,
b) across junctions between different *building* assemblies, and
c) around penetrations through the *building* assembly.
[7] *Ibid* at Part 5, Section 5.4, Sentence 5.4.1.2(4).
[8] *Ibid* at Volume 2, A-5.4.1.1, pp. A-60 – A-61.
[9] *Ibid* at Article 6.2.1.1., pp. 6-1. See also: Health Canada, "Radon: What you Need to Know," Newfoundland and Labrador Chapter of the Canadian Home Builder's Association (June 11, 2013), online: http://chbanl.ca/wp-content/uploads/2013/06/Health-Canada-Presentation.pdf
[10] *Ibid* at Volume 2, A-6.2.1.1., p. A-64. See also: Health Canada, "Radon: What you Need to Know," Newfoundland and Labrador Chapter of the Canadian Home Builder's Association (June 11, 2013), online: http://chbanl.ca/wp-content/uploads/2013/06/Health-Canada-Presentation.pdf
[11] *Ibid* at Subsection 6.2.2, 9.32.3. Requirements for ventilation, and mechanical ventilation systems, are laid out in Subsections 6.2.2. and 9.32.3.

Part 6 (Heating, Ventilating and Air-Conditioning)

Part 6, Article 6.2.1.1. (Good Engineering Practice) requires heating, ventilating and air-conditioning systems to be designed, constructed and installed in conformance with good engineering practice. Included in a list of examples of good engineering practice is EPA/625/R-92/016, "Radon Prevention in the Design and Construction of Schools and Other Large Buildings."[9]

The Appendix for Article 6.2.1.1. (Good Engineering Practice) discusses the differences in humidification and pressurization in new and existing buildings and provides recommendations with respect to pressurization requirements, as well as HVAC design/system changes. The Appendix also includes a section on radon control which references the federal Radon Guideline. It states: "[m]easures may be necessary to reduce the radon concentration to a level below the guideline specified by Health Canada. Further information on reducing the indoor concentration of radon can be found in the following Health Canada publications:

• "Guide for Radon Measurements in Public Buildings (Schools, Hospitals, Care Facilities, Detention Centres)," and

• "Radon: A Guide for Canadian Homeowners" (CMHC/HC)."[10]

Ventilation requirements are also discussed in Subsection 6.2.2. All buildings, except storage garages, are required to have mechanical ventilation, and natural ventilation is permitted in prescribed circumstances.[11] Natural ventilation or a combination of mechanical and natural ventilation can be provided in

a) *Buildings* of other than *residential occupancy* having an *occupant load* of not more than one person per 40m² during normal use,

b) *Buildings* of *industrial occupancy* where the nature of the processes contained therein permits or requires the use of large openings in the *building* envelope even during the winter, and

c) Seasonal *buildings* not intended to be occupied during the winter. [12]

[12] *Ibid* at Subsection 6.2.2, Sentence 6.2.2.2 (1) , p. 6-3.
[13] *Ibid*..
[14] Health Canada, "Radon: What you Need to Know," Newfoundland and Labrador Chapter of the Canadian Home Builder's Association (June 11, 2013), online: http://chbanl.ca/wp-content/uploads/2013/06/Health-Canada-Presentation.pdf
[15] *Supra* Note 2 at Volume 2, Division B, Appendix A, A-9.13.4, p. A-180.

16 *Supra* Note 14.
17 *Supra* Note 2 at Volume 2, Division B, Appendix A, A-9.13.4, p. A-180.
18 *Ibid*.
19 *Ibid* at Part 9, 9.13.4.2. (1), p. 9-82. See also Appendix A, A-9.13.4, p. A-180.
20 *Ibid* at Volume 2, Division B, Appendix A, A-9.13.4, p. A-180.

And buildings with non-residential occupancies may use natural ventilation if climatic conditions permit, if "engineering data demonstrates that such a method will provide the required ventilation for the type of *occupancy."*[13]

Part 9 (Housing and Small Buildings)

The majority of radon protection provisions appear in Part 9 (Housing and Small Buildings).
In the newest version of the NBC, air barrier requirements have been consolidated and prescriptive measures included on providing a rough-in for a future radon mitigation system. [14] Section 9.13 addresses measures for resisting the ingress of soil gases; Sections 9.18 and 9.25 include requirements for air and soil gas barriers in assemblies in contact with ground (and crawl spaces); Section 9.14. addresses the provision of control joints to reduce cracking of foundation walls and airtight covers for sump pits to reduce radon ingress. [15] Part 9 also includes new Appendix Notes and Illustrations. [16] These as well as other relevant sections are described below.
The Appendix to Part 9 states that various sections require the application of certain radon exclusion measures in all dwellings and that these measures are

- low in cost,
- difficult to retrofit, and
- desirable for other benefits they provide[17]

Radon exclusion is primarily accomplished by ensuring that the pressure difference across the ground/space interface is positive (air moves towards the outside) so that the inward flow of radon through any remaining leaks will be minimized. The requirements provided in Article 9.13.4.3 are explained in Appendix Note A-9.13.4.3.[18]
Subsection 9.13.4 addresses the leakage of *soil* gas from the ground into buildings. Resisting ingress of soil gases is required for all buildings.[19] The principal method to accomplish this is "to seal the interface between the soil and the occupied space, so far as is reasonably practicable." [20] Subsection 9.13.4 details protective measures to be taken to control soil gas ingress, and provides that, for dwelling units and residential occupancies, a rough-in for a radon extraction system must be provided. Sentence 9.13.4.2. (1) requires the installation of an air barrier system and addresses protection from all soil gases. The rest of Article 9.13.4.2., along with Article 9.13.4.3., which requires the provision of the means to depressurize the space between the air barrier and the ground, target the future mitigation of high radon concentrations.

21 *Ibid* at Part 9, Article 9.13.4.2., p. 9-82. See also Appendix A, A-9.13.4, p. A-180.
22 *Ibid* at Part 9, Subclause 9.25.3.1. (1) (b) (iii).
23 *Ibid* at Article 5.4.1.1. As discussed above, Article 5.4.1.1. requires that air leakage is controlled, or venting to the exterior permitted,[23] so as to:
a) provide acceptable conditions for the *building* occupants,
b) maintain appropriate conditions for the intended use of the *building,*
...
e) minimize the ingress of airborne radon from the ground with an aim to controlling the indoor radon concentration to an acceptable level, and
f) not compromise the operation of *building* services.
Sentences 5.4.1.1 (2) and (3) requires the installation of an air barrier to provide the principal resistance to air leakage except where uncontrolled air leakage will not adversely affect any of
(a) the health of safety of *building* users,
(b) the intended use of the *building,* or

(c) the operation of *building* services.
The Appendix to Part 5 (Article 5.4.1.1) notes that an air barrier system can reduce the likelihood of infiltration of dust and other pollutants which can lead to serious health or safety hazards. This Article requires the installation of an air barrier system in components and assemblies in contact with the ground to control the ingress of radon. The Appendix references the new Health Canada guideline of 200 Bq/m³ for indoor radon concentration, stating that "[m]easures may be necessary to reduce the radon concentration to a level below the Health Canada guidelineSee also Appendix Note A, A-5.4.1.1, pp. A-59 – A-60.

24 *Ibid* at Article 6.2.1.1. As discussed in the report, above Article 6.2.1.1. (Good Engineering Practice) requires heating, ventilating and air-conditioning systems to be designed, constructed and installed in conformance with good engineering practice. Included in a list of examples of good engineering practice is EPA/625/R-92/016, "Radon Prevention in the Design and Construction of Schools and Other Large Buildings." The Appendix for Article 6.2.1.1. discusses the differences in humidification and pressurization in new and existing buildings and provides

Sentences 9.13.4.2 (1) and (2) state:

1) All wall, roof and floor assemblies separating *conditioned space* from the ground shall be protected by an *air barrier system* conforming to Subsection 9.25.3.

2) Unless the space between the *air barrier system* and the ground is designed to be accessible for the future installation of a subfloor depressurization system, *dwelling units* and *buildings* containing *residential occupancies* shall be provided with the rough-in for a radon extraction system conforming to Article 9.13.4.3.

Subsection 9.25.3 addresses radon gas infiltration and requirements relating to air barrier systems. Subsection 9.25.3.1 includes requirements for barriers to air leakage and provides that air barrier systems separating conditioned spaces from unconditioned spaces or the ground must be a continuous barrier. Subclause 9.25.3.1. (1) (b) (iii) specified that the air barrier system must prevent air leakage from the exterior or ground inward "sufficient to … minimize the ingress of soil gas." [22]

For occupancies that are neither dwelling units nor residential occupancies, Sentence 9.13.4.2 (3) requires protection from radon ingress in conformance with

a) Article 9.13.4.3., or

b) Parts 5 and 6 (see Article 5.4.1.1.[23] and 6.2.1.1.[24]). [21]

recommendations with respect to pressurization requirements, as well as HVAC design/system changes. The Appendix also includes a section on radon control which references the federal Radon Guideline. It states: "[m]easures may be necessary to reduce the radon concentration to a level below the guideline specified by Health Canada. See also Appendix Note, A-6.2.1.1., p. A-64. See also: Health Canada, "Radon: What you Need to Know," Newfoundland and Labrador Chapter of the Canadian Home Builder's Association (June 11, 2013), online: http://chbanl.ca/wp-content/uploads/2013/06/Health-Canada-Presentation.pdf

25 *Ibid* at Volume 2, Division B, Appendix A, A-9.13.4.2 (3), p. A-181.

26 *Ibid* at Part 9, Sentences 9.13.4.3. (2) and (3), pp. 9-82 – 9-83.

27 *Ibid* at Volume 2, Division B, Appendix A, A-9.13.4.3, p. A-181.

28 *Ibid* at Volume 2, Division B, Appendix A, A-9.13.4.3, p. A-181.

29 *Ibid* at Part 9, Article 9.14.5.2. and Sentence 9.25.3.3(7).

30 *Ibid* at Part 9, Article 9.16.2.1, p. 9-95.

31 *Supra* Note 14.

Appendix A explains that since the federal Radon Guideline is established based on the time that occupants spend inside buildings, the installation of a means for the future removal of radon may not be required in buildings that are occupied by persons for less than 4 hours per day. Appendix A notes that radon problems in such buildings (or parts of buildings) may be addressed by providing a means for increased ventilation. [25]

Article 9.13.4.3. requires that a rough-in for subfloor depressurization is provided for floors-on-ground. Requirements relating to what the system must consist of are provided, and these include:

a) a rough in of a gas permeable layer, or

b) clean granular materials and a pipe

Detailed requirements for both (a) and (b) are provided in 9.13.4.3. (2) and (3).[26]

Appendix A clarifies that Subsections 9.13.4.3. (2) and (3) contain two sets of requirements. Sentence (2) describes criteria using performance-oriented language, and Sentence (3) describes one acceptable solution using prescriptive language. Appendix A notes that some cases may require a solution other than that described in Sentence (3).[27] Appendix Note A-9.13.4.3.(2)(b) and (3)(b)(i) of Appendix A provide detailed recommendations for the design of the rough-in to ensure effective depressurization from the extraction system.

Appendix A also addresses the completion of a subfloor depressurization system, and indicates that so doing may be necessary to reduce the radon concentration to a level below the guideline specified by Health Canada.[28]

Article 9.14.5.2. requires sump pits covers to be designed to be airtight (in accordance with Sentence 9.25.3.3(7) such that any clearances are sealed to prevent air leakage.[29]

Article 9.16.2.1 also addresses soil gas control with respect to floors-on-ground by providing the requirement that granular material be installed under floors-on-ground (except for under “slabs in garages, carports or accessory buildings, or buildings of industrial occupancy where the nature of the process contained therein permits or requires the use of large openings in the building envelope even during the winter.”[30] Note that in the newest version of the NBC, the Subsection 9.16 exemption with respect to fill under slab has been deleted. [31]

Subsection 9.25.3 (Air Barrier Systems) addresses radon gas infiltration. Article 9.25.3.1. requires an air barrier system to prevent air leakage for “wall, ceiling and floor assemblies separating conditioned spaces from unconditioned space or from the ground”. The barrier must be “continuous” and sufficient to “minimize the ingress of soil gas.”[35]

Article 9.25.3.4 addresses soil gas control of walls in contact with the ground, and subsection 9.25.3.6 addresses soil gas control with respect to floors-on-ground.[36]

Appendix A discusses the Air Leakage and Soil Gas Control Requirements of Part 9. Appendix Note A-9.25.3.4 and A-9.25.3.6 (Air Leakage and Soil Gas Control in Floors-on-Ground) note that provisions on sealing of penetrations found in Subsection 9.25.3.3. (6) apply equally to hollow metal and masonry columns penetrating the floor slab. The Appendix also notes that Subsection 9.25.3.6.(6) requirements on drainage openings in slabs can be satisfied with a variety of devices that prevent the entry of radon and other soil gases through floor drains.[37]

The Appendix to Sentences 9.25.3.6 (2) and (3) also notes that “[f]loors-on-ground separating conditioned space from the ground must be constructed to reduce the potential for the entry of air, radon or other soil gases”. The Appendix indicates that this is often done with a layer of polyethylene under the floor, and provides a discussion on best practices to avoid cracking of slabs-on-ground. [38] [32]

Note that in the newest version of the NBC unheated crawl spaces and accessible heated crawl spaces without slab are exempted.[33]

Under Section 9.18, Article 9.18.6.2 heated crawl spaces are required to have a ground cover that is sealed to the foundation wall, and all penetrations sealed against air leakage.

32 *Supra* Note 2 at Volume 2, Division B, Appendix A, Article 9.18.6.2, p. 9-99 – 9-100.

33 *Ibid* at Part 9, Articles 9.13.4.2., 9.18.6.1. and 9.18.6.2.

34 *Supra* Note 14.

35 *Supra* Note 2 at Part 9, Article 9.25.3.1., p. 9-154. The air barrier properties, it’s continuity of design, and air leakage control in masonry walls and underground roofs are dealt with in Articles 9.25.3.2. – 9.25.3.5 at pp. 9-154 – 9-155.

36 *Ibid* at Part 9, Subsection 9.25.3, pp. 9-154 – 9-155.

37 *Ibid* at Volume 2, Division B, Appendix A, A-9.25.3.4 and 9.25.3.6. at p. A-203.

38 *Ibid* at Volume 2, Division B, Appendix A, A-9.25.3.6 (2) and (3), p. A-204.

Air barrier requirements which appeared in Section 9.13 past versions of the NBC are now in Section 9.25. These include:

– For below-ground walls
– Polyethylene soil gas barrier required under slab
– Slab perimeter sealed to air barrier of the wall
– All penetrations sealed.[34]

Appendix C – Supplementary Material for Chapter 4

References for Table 7 in Chapter 4

Province	References
Labrador and Newfoundland	(Dunn and Cooper 2014)
PEI	(Dunn and Cooper 2014)
Nova Scotia	(Dunn and Cooper 2014)
New Brunswick	(Dunn and Cooper 2014)
Quebec	Principaux changements au code de construction du Quebec, 2009 (Régie du batiment Québec 2009)
Ontario	https://www.e-laws.gov.on.ca/html/source/regs/english/2012/elaws_src_regs_r12332_e.htm#
Manitoba	(Dunn and Cooper 2014)
Saskatchewan	(Dunn and Cooper 2014)
Alberta	(Dunn and Cooper 2014)
British Columbia	B14-07 (Building and Safety Standards Branch 2014)
Nunavut	(Dunn and Cooper 2014)
Northwest Territories	(Dunn and Cooper 2014)
Yukon	(Dunn and Cooper 2014)

BC Radon-prone area (Building and Safety Standards Branch 2014)