

ASSESSMENT OF LUNG CANCER RISK REDUCTION BEFORE AND AFTER
ADOPTION OF A RADON RESISTANT NEW CONSTRUCTION (RRNC)
BUILDING CODE STANDARD IN AMITY TOWNSHIP, PA

By
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A dissertation submitted to the Johns Hopkins University in conformity with the
requirements for the degree of Doctor of Public Health

Baltimore, Maryland
June 2019

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Abstract

Radon 222 (^{222}Rn) is an element found in the soil surrounding many homes in the United States. It is formed during the natural radioactive decay of uranium. Radon gas moves into homes through cracks or holes in the foundation and can then be inhaled by the home residents. Inhaled radon is the second leading cause of lung cancer after smoking and is the leading cause in non-smokers. Radon-Resistant New Construction (RRNC) reduces residential radon exposure and reduces the risk of developing lung cancer. Several townships and municipalities in Pennsylvania have adopted ordinances that require new houses to be built using RRNC. To evaluate the effectiveness of RRNC in reducing radon-related lung cancer risk, residential radon concentrations were compared in homes with and without RRNC in a Pennsylvania township that has adopted the RRNC statute into their building codes.

This study utilizes a risk-based decision framework to assess the lung cancer risk reduction in Amity Township, PA after adoption of a RRNC standard. The work primarily uses data on residential radon measurements that have been compiled by the Pennsylvania Department of Environmental Protection (PADEP). These measurements are reported to the PADEP by certified testers and homeowners. The results from the initial analysis on the radon concentrations will be used in a peer-reviewed lung cancer risk model to examine the reduction in risk for residents of RRNC homes versus non-RRNC homes. This work also uses publicly available measurable characteristics of health indicators such as lung cancer incidence and mortality collected from and/or about Amity Township, PA. Because the smoking rates were not available down to the township level, the smoking rates of Berks County, PA (where Amity Township is

located) will be utilized. The health and economic benefits of adopting an RRNC standard will also be reviewed as part of the decision process.

Dissertation Readers

Paul Locke, DrPH, JD, MPH, (advisor), Takeru Igusa, PhD, (chair), Ernst Spannhake, PhD, Mary Fox, PhD, MPH, Tobie Bernstein, JD.

Acknowledgments

To Dr. Locke and all at the Johns Hopkins School of Public Health, Department of Environmental Science, for not only taking a chance on me, but for helping me along the way. For my Aunts (Anne and Susan) and Uncles (Charlie and Warren), stepping up as surrogate parental support. For Dawn R., Missie V. and the rest of the running/triathlon (Bryan, Danielle, Cecilia, Chrissy, Richard et.al.) village, thank you.

Dedication

To my husband, Mark and my children, Samantha, Isaac and Leila, for supporting me and putting up with me, while I obtained my education.

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Chapter 1: Introduction

Americans are exposed to ionizing radiation through a variety of sources. These can include medical procedures such as X-rays and computerized axial tomography (CAT) scans, ubiquitous background, consumer products, and occupational exposures. Residential radon is the largest portion of ubiquitous background exposure, and the second largest single source of Americans' radiation exposure, behind the total combined categories of all medical procedures ¹.

Radon is a known human carcinogen, and according to the EPA and the Surgeon General of the United States, exposure to radon gas is the second leading cause of lung cancer, behind cigarette smoking, and the leading cause of lung cancer among non-smokers ^{2,3}. This is based on multiple epidemiological studies of underground miners exposed to high concentrations of radon, residential studies of individuals exposed to lower concentrations of radon and research carried out on experimental animals ^{4,5}.

While smoking or radon gas exposure can independently increase an individual's risk of developing lung cancer, exposure to both greatly enhances the smokers' risk of developing lung cancer. In a study, Barros-Dios et al., 2012 ⁶, found that the level of interaction between the two risks increased as the residential radon concentration increased and called this a synergistic effect. This means that the risk of developing lung cancer is greater for smokers exposed to increasing levels of residential radon gas and that the risk is greater than adding the risks together. However, the risk is sub-multiplicative: it is less than expected if the two risk factors were multiplied together. The trend in relative risk of developing lung cancer for both smokers and non-smokers were similar with increasing exposures to residential radon. As both populations are exposed to increasing residential radon gas, their risk for developing lung cancer also

increases. The excess absolute risk of developing lung cancer due to residential radon exposure is much higher in smokers than non-smokers, due to the smokers' higher baseline risk of lung cancer from smoking ⁷. Please see Appendix A for definitions of the different risk measurements used.

While not everyone exposed to elevated residential radon concentrations will develop lung cancer, the higher the level of exposure, the greater the risk or chance that an individual has for developing the disease. A home built with radon resistant new construction (RRNC) provides a simple way to reduce the levels of radon gas in the home. RRNC incorporates a passive radon mitigation system into a home as it is built. A passive mitigation system consists of a vent pipe that extends from the house foundation to above the roof and an electrical junction box in the attic by the vent pipe. The junction box allows for the ability to install an electrical source for a fan, to easily convert the system from passive to active if additional radon gas ventilation is needed. A home with RRNC will reduce levels of radon by providing the ability to vent the gas for the life of the home. Reduced concentration of radon gas reduces a person's overall exposure and therefore reduces a person's risk for developing lung cancer. Adoption of required radon resistant building methods for new home construction will help lower the levels of radon, and thus reduce the risk of lung cancer for that population ⁸.

Considering the fact that reducing exposure to radon reduces the risk of developing lung cancer, the data examined in this dissertation, from Amity Township, PA will show that adoption of radon resistant new construction is an effective way of reducing residential radon exposure, thereby reducing the risk of developing lung cancer. But, for development of policies or for evaluating the effectiveness of RRNC, this data by

itself is not enough. For the development of regulation and policies, the cost, benefits and reduction in health risks in homes built with radon resistant features must be evaluated in comparison to homes built without these features.

To better do this evaluation, this study approximates a risk-based decision framework. The three phases of the risk-based decision framework are: Phase I: Problem Formulation, Phase II: Risk Assessment and Phase III: Risk Management.

Phase I will describe what radon gas is and why exposure to radon gas is a health risk. Phase II will assess effectiveness of RRNC to reduce residential radon gas exposure and determine reduction in the lung cancer risk from the reduction in homes built RRNC compared to homes built without RRNC in Amity Township, PA. Phase III is the risk management or decision phase in which the benefits and costs are reviewed for their risk-reduction potential (the health and economic benefits of adopting RRNC when it comes to lung cancer). Chapter 1 will fully cover Phase I and review the aims and objectives of Phase II and Phase III. Chapter 2 will address phase II aim 1, Chapter 3 will address Phase II aim 2, and chapter 4 will address Phase III aim 3 and aim 4.

Phase I Determining and defining the health hazards from residential radon exposure.

Background and Significance of Radon Gas:

Radon is part of the family chemical elements called noble gases; noble gases are inert and do not chemically react. As shown in figure 1.1, radon is produced during the natural radioactive decay of uranium found in rock and soil ⁴.

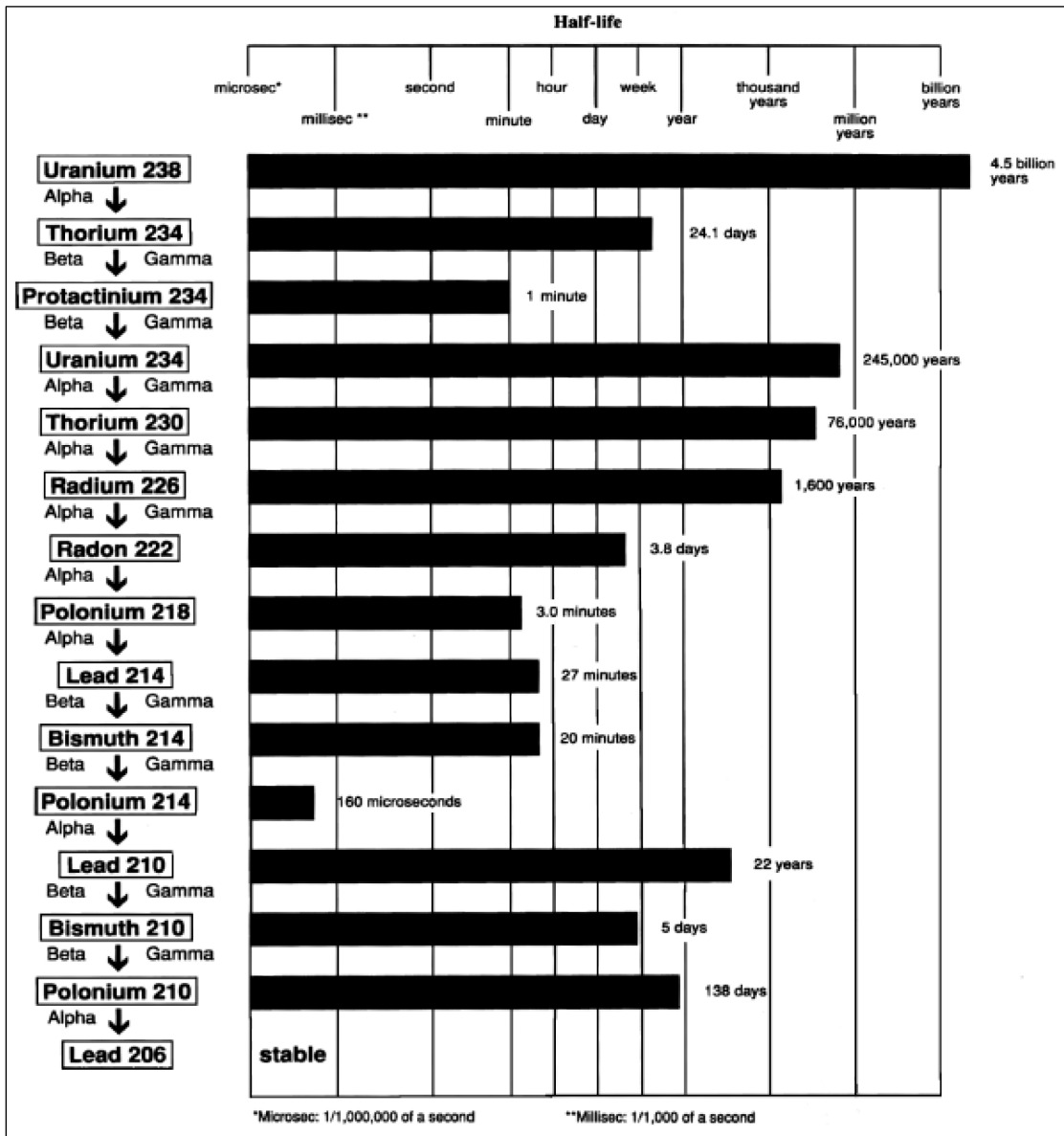


Figure 1.1 Uranium-238 Decay Chain-with Half-Life and Particle Emissions.
 Downloaded from the Canadian Coalition for Nuclear Responsibility on 06/04/2015.
http://www.ccnr.org/decay_U238.html

Radon was discovered and called “Radium Emanation” in 1900 by German chemist Friedrich E. Dorn, while the actual isotope radon 222 (^{222}Rn) was first observed by British Scientist R.B. Owen and New Zealand scientist Ernest Rutherford in 1899⁹. The ^{222}Rn isotope, one of radon’s most stable isotopes, has a half-life of 3.82 days. However, the isotope will continue to decay, the additional products of the decay process are called progeny. Most of the respiratory health risks to humans are caused by exposure to these progeny of ^{222}Rn ³. Some of the radioactive progeny include polonium (^{218}Po) and bismuth (^{214}Bi)¹⁰. Unlike ^{222}Rn , these are solid airborne particles that can attach to dust and can be easily inhaled and retained in the lung tissue. Damage to the lung tissue can occur from the radioactive energy from the particles that attach to the tissue or from the energy as the particles continue to decay.

^{222}Rn and its progeny are all ionizing radiation alpha particle emitters. There are three forms of ionizing radiation particles, alpha (α), beta (β) and gamma (γ). Alpha particles are formed when a pair of electrons is lost from a helium atom, resulting in a positively charged particle. These particles do not travel far and have minimal ability to penetrate. The limited ability to penetrate means clothing or a single piece of paper can serve as effective shields. Alpha particles are also known as densely ionizing radiation, or high linear energy transfer (LET) radiation. In general, these particles have greater relative biological effectiveness (RBE), compared to beta and gamma particles¹¹. RBE is one of the ways to describe and compare how the various kinds of radiation cause biological damage to tissue or DNA. The increased RBE is due to how the alpha particle deposits a unit of energy.

One of the main reasons for the increased RBE is due to the alpha particles' limited mobility and penetration in the lung, therefore the concentration of the energy remains in a smaller area (less area to dilute the energy's effects.) Alpha particles thus deposit a larger amount of radiation to a smaller area resulting in greater biological damage and a higher risk of cellular, tissue and DNA damage.

Beta radiation particles are high energy electrons or positrons; the particles charge will depend on the type of decay that occurs. The decay product can have a positive or neutral charge depending on particle. They can travel several feet and require more shielding than alpha particles for protection. Gamma particles, also known as gamma rays, are very high energetic photons. They are emitted from the nucleus of an unstable radioactive atom. Due to the high energy, these particles can travel much further than alpha and beta particles. Because gamma particles have increased penetration ability, effective shielding requires very thick plates of lead.

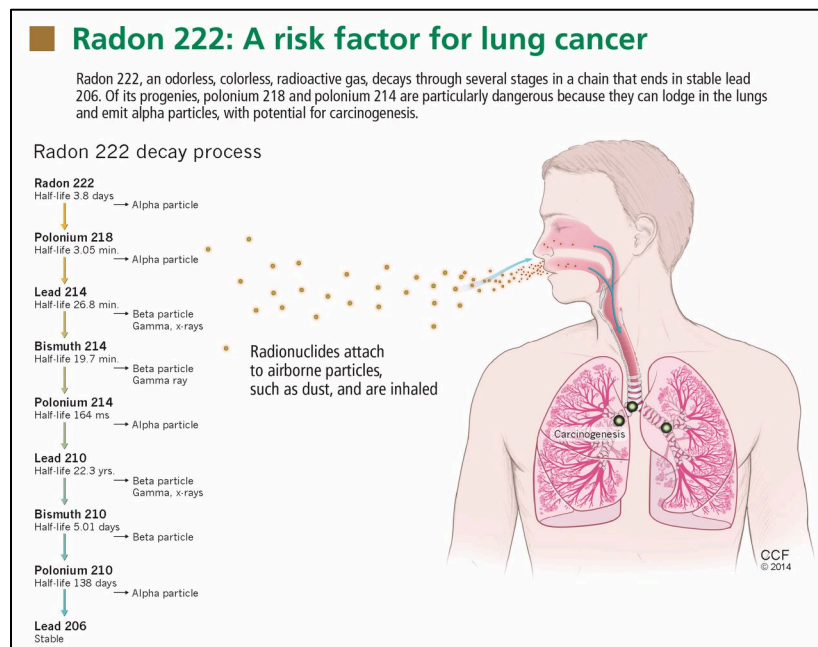


Figure 1.2 Radon 222 decay chain through several intermediate steps to the stable isotope Lead 206¹²

All the products of radon decay are alpha (α)–emitters and have varied half-lives (Figure 1.1). The half-life is the time required for half of the material to decay and become another radioactive element; these products of decay are also identified as the elements' progeny. Decay means the element is losing mass in the form of the alpha particle; the loss of alpha particle is converted into energy. It is this energy that can potentially harm lung tissue. Due to their positive charge, the radon progeny have the capacity to attach to aerosol particulates such as household dust¹³. Figure 1.2 from Choi and Mazzone, 2014, shows the decay chain from ^{222}Rn to the stable lead isotope lead 206 ^{206}Pb and the potential for the radionucleotides to attach to airborne particles¹². An additional health risk exists due to their limited ability to penetrate and travel; once inhaled in the human respiratory system, they are deposited in a location such as lung tissue. The particles do not travel far into the lung tissue. If they attach to lung tissue, they tend to stay there. This radioactive particle embedded in the cellular tissue of human lungs can further decay, releasing more energy, and increasing the potential risk of both cellular protein and cellular DNA damage occurring. If cellular repair is unsuccessful, the cell may begin to divide without regulation. Unregulated cell division can lead to potentially cancerous tumor formation¹⁴.

Health risks from exposure to radon gas

The lung cancer risk from exposure to residential radon gas has been well established. In 1988, the Environmental Protection Agency (EPA) and the United States Public Health Service (USPHS) issued a public health advisory urging homeowners to test their homes for radon gas^{15,16}. On January 13th, 2005, Dr. Richard Carmona issued the first national health advisory as the Surgeon General of the United States on the risks

of “breathing indoor radon gas” and he urged Americans to prevent the buildup of the gas to dangerous levels ². In 2009, the acting Surgeon General, Dr. Steven Galson, wrote about the benefits of radon reduction to promote healthy homes ¹⁷. The well-established relationship of smoking and lung cancer is widely known and accepted, and this relationship is the largest cause of lung cancer. However 10 to 15% of lung cancer occurs in individuals who have never smoked ¹⁸. While there are several known causes of lung cancer in non-smokers, radon is the leading cause of lung cancer in non-smokers. It is therefore the second leading cause of cancer behind cigarette smoking ^{2,6,14}. While some data may suggest an association of childhood leukemia and residential radon exposure, additional research in this area is needed before this can be confirmed ¹⁹. At this time, no cancer has been conclusively linked with exposure to radon other than lung cancer ⁸.

In 2018, 11.6% of the world’s total cancer incidence - 2.1 million cases - were new diagnoses of lung cancer which is equal to the incidence of breast cancer. However, there are more deaths from lung cancer than from other cancers, causing 18.4% or 1.76 million of all cancer deaths in the same year ²⁰. It is one of the most aggressive cancers with a 5 year survival of only 16% ^{2,6,14}. Cigarette smoking causes 85% to 90% of lung cancer cases, which means between 160,000 to 240,000 of the world’s new cases in 2008 were not due to cigarette smoking ²¹. Based on the lung cancer incidence in 2018, the world lung cancer incidence due to radon is estimated to be 210,000 to 315,000.

Epidemiological evidence based on underground miners and residential case control studies have found that increasing exposure to radon gas will increase a person’s risk for developing lung cancer ^{7,10,13,22}. In research studies, animals exposed to radon

gas also showed increased risk for forming lung tumors. Studies in rats have shown that the effect of the dose rate differs from very high radon concentrations to very low radon concentrations. The dose from low concentrations, when reducing the concentration or increasing the time over which the dose is delivered decreases the risk of lung tumor development. However, at values above 50 Working Level Months (WLM), measure of occupational radiation exposure of underground miners, there is increased risk of tumor formation when reducing the concentration or increasing the delivery time²³. The Working Level (WL) is a measure of potential alpha particles per liter of air. The WLM is equivalent to being exposed to the WL for 170 hours (typical number of hours worked by a miner per month.)²⁴ This is known as “dose and dose-rate effectiveness factor” (DDREF)¹¹. When the animals were exposed to a combination of cigarette smoke and radon gas, the risk of tumor formation increased⁵.

Mechanism of radon carcinogenesis

Knowledge of the mechanisms of cell damage caused by the alpha particles has been increasing. Since alpha particles are more massive and more highly charged with energy localized and absorbed in a single location, they are more damaging to living tissue than other types of ionizing radiation.

The largest contributor to the lung cancer risk is not from the exposure to radon gas, but from the exposure to the radon decay products known as radon progeny. Due to the positive charge of the alpha particles, they tend to attach to dust particles. While both dust-attached and free-floating particles can be inhaled, the dust attached particles are better at clinging to respiratory epithelium, while the free-floating particles are more easily cleared from the body. The size of the attached dust particles will affect how deep

into the lung tissue they can penetrate. Radon progeny particles have been shown to directly damage the lung tissue ⁴. While most radon particles are exhaled, increased exposure increases the potential for some of the radon to remain in the lung tissue. Upon inhalation, particles move along the respiratory tract as follows: air (along with any particulates) flows along the trachea, which then divides into the right and left bronchi, from the bronchi, air then enters the lungs. Within the lungs, the air particles further divide among branches called bronchioles, each of these bronchioles terminates in a cluster of alveoli. Due to the average particle size of lung carcinogens such as the dust attached radon particles, the site of most lung cancer is within the bronchial epithelium ^{12,25}.

Lung deposition is how much of the radon settles into the lung tissue. The deposition is based on exposed dose, the number of particles inhaled (retention) and the number of particles that attach to lung epithelium (deposition). Particles that do not attach to the lung epithelial cells are exhaled and leave the body. The amount deposited depends on multiple factors such as: radon particle size, lung capacity, tidal volume (volume of air inhaled), respiratory rate, etc. Due to their size, movement of radon particles within the respiratory tract is by Brownian diffusion (random motion that occurs when radon particles collide with gas molecules) that can lead to contact and deposition on respiratory surfaces ²⁶.

Once deposited in the lung tissue, radon progeny can continue to decay and emit high energy. This, in combination with the localized focal point for the energy, means increased risk for tissue, cell and DNA damage and increased risk for development of cancer ⁴. Development of lung cancer is a multi-step process that takes place over several

years between the exposure to a carcinogen and the development of diagnosed cancer. When a person does develop the disease, lung cancer is one of the more aggressive cancers with a very high mortality rate. According to the 2018 Facts and Figures from the American Cancer Society, the incidence of lung cancer is in 2nd place following prostate incidence in males and breast cancer incidence in females. However lung cancer was the leading cause of cancer deaths in both males and females causing about 25% of the cancer deaths in both ²⁷.

The energy from the alpha-particles generates damage to the cells both directly and indirectly. Direct damage occurs when the energy from the alpha particles disrupt the cellular DNA or indirectly by breaking the molecule bonds of proteins in the cell. Indirect damage occurs through generation of free radicals. Decay of alpha-particles results in the ejection of electrons from water, generating several reactive species leading to cellular damage by hydroxyl radical attack which ionizes the water molecules within the cell. Ionizing the water molecules produce free radicals which can potentially cause further damage to the cells' ¹⁴. As the radon progeny continue to decay, the indirect and direct damage cycle to the cellular DNA can keep occurring. This increases the chances that cellular repair may happen incorrectly or not at all ²⁸. Lab studies have shown that at the cellular level, radon progeny have been shown to cause chromosomal damage and other types of cellular damage ²⁹. While DNA damage may occur, if the repair is not proper or is incomplete, the cells are then at risk for carcinogenesis ^{14,30}.

As previously described, alpha radiation travels only extremely short distances in the body. Thus, alpha radiation from decay of radon and its progeny in the lungs cannot reach cells in any other organs, so it is postulated that lung cancer is the most likely

cancer hazard posed by radon. An alpha particle emitted from radon progeny decay is in the form of a high-energy helium ion, He²⁺. These helium particles transverse cell nuclei in a linear pattern and deposit energy in a linear path. LET, otherwise known as Linear Energy Transfer, refers to the energy transferred per unit of path traveled by the ionizing particle. Since alpha particles travel short distances and are slow compared to beta and gamma particles, their efficiency in transferring energy and affecting genomic change is very high, as is their LET quantity. Once deposited, this energy causes DNA alterations, cell cycle stress, and occasional cell death.

Epidemiological studies

Epidemiological studies of populations in various environments have linked lung cancer to radon exposure. Early studies show that uranium miners exposed to high concentration of radon gas have an increased risk of developing lung cancer^{10,13}. Even before this, reports of “wasting disease” were seen in miners as far back as the 16th century¹³. A pooled analysis of residential radon studies in both Canada and the United States was carried out^{7,22}, as were studies of underground miners⁴. By combining the data from these studies, researchers were able to examine data from thousands of people. The results of this analysis demonstrated increased risk of lung cancer for individuals with prolonged exposure to household (residential) radon at elevated levels and for miners exposed to much higher concentrations of radon gas during shorter occupational timeframes. This increased risk in homes was consistent with the estimated level of risk based on epidemiological studies of underground miners^{12,31,32}.

In a collaborative analysis of 13 residential radon and lung cancer case control studies in Europe, Darby⁷ found that the risk of lung cancer increased as the mean

concentration of residential radon increased. The study found that the risk of lung cancer increased by 8.4% when radon concentration increased by 100 Bq/m³ (about 2.7 pCi/L.) Both Becquerels per cubic meter (Bq/m³) and picocuries per liter (pCi/L) are used to measure the concentration of radiation activity or rate of decay in air. One pCi/L is equivalent to 37 Bq/m³.

Krewski²² also carried out a pooled residential study in North America that showed exposure to increasing radon concentrations increased a resident's lung cancer risk. Similar to the results from Darby, lung cancer risk increases by about 8 % when radon concentration increases by 100 Bq/m³. By combining residential radon studies in the pooled analysis in the North American (Krewski) and European (Darby) studies, both Darby and Krewski were able to evaluate a larger residential sample set while comparing individuals with lung cancer versus those without lung cancer. In the Darby analysis, they also had detailed smoking history which enabled their ability to stratify for current smokers, non-smokers and individuals who have quit smoking⁷. A paper by Barros-Dios⁶ showed that individuals exposed to concentrations higher than 50 Bq/m³ are at a 2 fold higher risk for lung cancer. This was based on a case control study using hospital patients in Spain which had a total of 990 individuals (442 cases and 548 controls.) Of these, only 862 had radon measurements taken of their home. This two-fold risk was seen after they stratified for multiple variables such as study, age, gender and smoking risk.

In 2003, EPA carried out a risk assessment and found that radon contributed to 21,000 lung cancer deaths in the US¹⁴. Most of these individuals were smokers, but 3,000 of the deaths were in non-smokers. The study also noted that lifelong non-smokers

exposed to radon levels above 4 pCi/L could be responsible for about 7 individuals in 1,000 getting lung cancer and that reducing the radon concentration to 2 pCi/L would reduce the chances to about 4 individuals in 1,000 getting lung cancer. Exposure to 4 pCi/L of radon concentration during an average lifespan for current smokers could cause between 62 individuals out of every 1000 to develop lung cancer, reducing the exposure to 2 pCi/L would reduce the number of individuals who could get cancer to 32 out of 1,000. In Biological Effects of Ionizing Radiation (BEIR) VI, the National Research Council found that lung cancer deaths per 1000 non-smokers ranged from 15 to 50 people with exposure to radon concentrations of 4 pCi/L. The number of deaths per 1000 non-smokers drops down to a range of 7 to 30 people when people are exposed to radon concentrations of 2 pCi/L ⁴.

Using lung cancer mortality statistics and data from France's census in a 1999 paper by Catelionois, it was determined that 25,134 individuals in France died from lung cancer. Catelionois calculated that 2.2% to 12.1% of these deaths were due to exposure to radon gas ³³. The range was based on using multiple risk models such as BEIR and Darby. In Canada, the percentage of all lung cancer deaths due to radon is approximately 10% ³⁴.

The BEIR VI study was initiated to better determine the risk of lung cancer from exposure to residential radon. The committee of 13 scientists decided to build their risk model report based on epidemiological data from 13 studies on underground miners. However, when they created their models, they had to account for the fact that the data came from populations (underground miners) that are different from the population (home residents) in question. They created risk models based on high concentration

exposure of the miners and after making corrections based on assumptions about the differences between miner populations and home residents, extrapolated the information to determine the risk of low-level exposure to home residents.

International Commission on Radiological Protection (ICRP) report 115³⁵ agreed that the risk estimates for residential exposure are consistent with those estimated for underground miners who experienced low levels of exposure. Its analyses show good consistency between lung cancer risk estimates obtained from miner studies and indoor studies. Previous ICRP reports had calculated doses based on conversion data from underground miners, but in the most current report they do not recommend this approach. ICRP currently recommends using a dosimetric (calculating the absorbed dose by targeted tissue) approach to calculate the effective dose a person or a population receives. This could potentially lead to the ability to approximate dose estimates for individuals.

Both the BEIR VI and ICRP 115 agree that the epidemiological studies, whether from underground miners or residential radon exposure, show that exposure to radon progeny can cause lung cancer and that there is no convincing evidence that exposure to radon is associated with any other type of cancer.

The Darby study and BEIR VI both have shown that even in the absence of smoking, radon exposure is a lung carcinogen. When comparing the risk of exposure to different residential radon concentrations, both studies found that the risk of lung cancer is linear and that it increases with increasing radon concentration. Due to lower baseline lung cancer risk, the relative risk due to increasing residential radon is higher in non-smokers versus smokers. However, due to the dominant effect of tobacco, the excess absolute risk of developing lung cancer (the actual risk of developing a disease) is greater

in smokers exposed to the same concentration of radon versus non-smokers. With respect to the lung cancer risk, there is interaction between exposure to both radon gas and smoking. For the smoker exposed to radon gas, the risk for lung cancer increases sub-multiplicatively. This means the risks are greater than what would be expected from the risks being additive but less than what would be expected if the risks were multiplied²⁶.

How the problem of residential radon became a known hazard

The health risk from exposure to radon gas was a known problem for underground miners for many years. However, the problems of residential exposure to radon came to the attention of many in the United States due to the problems faced by a Pennsylvanian home owner, Stanley Watras. Mr. Watras was a civil engineer working at the Limerick Nuclear Power plant. One day, while entering the plant, radioactive detectors went off due to the high levels of radioactive material on Mr. Watras's clothing. The source of the radioactive contamination was found to be coming from Mr. Watras's home, which had been built on bedrock that contained uranium ore, in Boyertown, PA located in Berks County³. The average radon levels in the home were found to be about 2,750 pCi/L¹⁰ However, after remediation using sub-floor ventilation, levels were brought down to 4 pCi/L or below. After remediation, Mr. Watras and his family remained in the home and eventually he started his own testing and radon remediation business¹⁰.

Environmental Factors that Affect Residential Radon Concentrations

United States Residential Radon Distribution

After discovering high levels of radon in the Watras home and other homes in Pennsylvania, the EPA began a nationwide assessment of radon exposure in the United States. From this assessment, the EPA found that levels of radon in US homes shows a non-normal distribution.

According to the National Residential Radon Survey conducted in 1991, the average arithmetic indoor radon concentration in United States was 1.3 pCi/L³⁶. The survey also found that most of the homes have radon concentrations close to zero, but some of the homes have extremely high radon levels. When graphed, the distribution of radon would be skewed with the peak at the low concentrations and a long tail to the right due to the few homes with the high radon concentration. In addition, if one were to log transform and then graph the residential radon concentrations, the values would appear like a normal bell curve. This is called a log-normal distribution, and in this type of distribution, using the more common arithmetic mean value as a central tendency measure would not be the most accurate measurement but it is the one that is typically used.

In analyzing and describing data distributions, measures of central tendency are used to determine a single value that represents the middle of the distribution. The three most common measures of central tendency are the arithmetic mean, median and mode. In a normal distribution, the mean, median and mode are equal. The mean in this type of log-normal distribution would be higher than the median (the middle value.) The arithmetic mean, also known as the average, is found by obtaining the sum of the data set

divided by the number of data points. While simple to do, the arithmetic mean is strongly influenced by outliers. In short, in the non-normal distribution of radon in US homes, an arithmetic mean is not the best measurement for statistical evaluations.

When graphed, the high home concentrations or outliers which cause the non-normal distribution, will display as skewed or as a tail. When averaged, these high radon concentrations have a strong effect on the arithmetic mean. Because of the non-normal distribution, using the arithmetic mean could under or overestimate the average residential radon exposure. Log-normal distribution of indoor radon concentrations has been well documented³⁷⁻³⁹. The more accurate measure of central tendency for a log normal distribution is the geometric mean. The geometric mean is the inverse log of the mean of the log-transformed values. When log transformed, residential radon data appear normal. The geometric mean is more resistant to the effect of outliers because the residential radon concentrations are logarithmically transformed. This reduces the spread and the effect that outliers have on the logarithmic mean⁴⁰.

Factors that potentially increase the radon levels in homes

Any residential structure can contain high levels of residential radon; certain factors can increase the likelihood that a home can accumulate radon gas. The three most important factors are soil composition, radon mobility and the home structure.

Soil Composition

Some rocks found in the soil have higher than average uranium content (light-colored volcanic rocks, granites, dark shales, sedimentary rocks that contain phosphate)^{13,41}. The radon concentration in the soil that surrounds the rocks that contain higher levels of uranium tends to have the same radon levels. The rocks break down and

eventually become components of the soil. Based on these factors, the EPA created a radon exposure potential map of the US, with areas divided into 3 levels of risk. Homes in areas considered to be level 1 (predicted average indoor radon screening level greater than 4 pCi/L) are at higher potential risk to have high residential radon levels. While these geographic factors (mineral composition of soil and/or levels of granite in the environment) can increase the chances of having soil that emanates radon, there are other factors such as the ability for the radon to move through the soil that are important.

(Information and a link to the EPA radon zone maps can be found at:

<http://www.epa.gov/sites/production/files/2015-07/documents/zonemapcolor.pdf>.)

Radon Mobility

The rate in which radon can move through the soil depends on the amount of water in the soil, and pore space (how crumbly the soil is.) Movement through the soil will change the length of time that areas are exposed before the radon decays. Soil that is more permeable, such as soil that contains higher levels of coarse sand or gravel, allows for easier movement of radon throughout the soil. The radon will move from the soil and then dissipate into the atmosphere or can collect in a confined structure such as a home or a mine^{26,42}.

Home construction characteristics:

Air in soil (with or without radon) will flow towards a home foundation. This is due to differences in air pressure levels between the soil and the house foundation.

Homes in certain locations may be at higher risk for having high levels of radon due to higher levels of soil radon concentrations, but homes in areas of low soil concentrations can also have high concentrations of radon and vice versa. Certain home features also

increase the risk for radon accumulation such as cracks in the foundation^{32,43}. The gas has the ability to move through a home's foundation from the soil that surrounds it. Homes with basements (the soil surrounds the structure that is below ground), homes with walls below grade, homes with exposed earth floors, homes built with hollow concrete block basements (versus poured cement), and homes with foundation cracks are all features that put a home at increased risk for radon accumulation. Radon gas gets into homes through cracks in the foundation or other openings in the home's lowest points. Basements set below the ground level provide more surface area for the gas to move from the surrounding home and into the house. The gas will then rise from the basement to other levels in the home. Once the gas collects in the home, the residents can then inhale the gas, or the radon progeny attached to dust particles.

The gas has the ability to accumulate in homes and because radon gas is heavier than air it tends to collect in lower confined places such as in the basement of a home. Because radon gas is heavier than air and tends to collect in lower places such as in the basement of a home where Due to the multiple factors affecting residential radon levels such as soil concentration and home construction, homes sitting side by side can have very different residential radon levels. The only way to know the levels is to have the home tested^{9,13}. Therefore, it is prudent to have all homes tested regardless of radon ground level concentrations surrounding it. Testing individual homes is the only means of reliably getting measurements of the home's indoor radon level.

Reducing lung cancer risk by reducing radon exposure through RRNC

The radon element identified by its atomic weight as radon 222 (^{222}Rn) is a gas, and a part of the uranium-238 decay chain. Radium-226, its precursor, is ubiquitous in

the earth's crust and as a result produces a continuous source of radon. Due to the continual decay of uranium-238, radon and its decay products will always be found in the soil. Since the soil will never be radon free, the most effective way to prevent residential radon exposure is to build homes that can reduce potential radon concentrations. This modification is known as radon resistant new construction (RRNC).

Properly built radon resistant new construction is a relatively inexpensive way to reduce radon levels and while one can install a system after the home is built, it can be up to 3 times more expensive to modify a home after it is built ⁴⁴. Radon resistant new construction reduces radon levels by venting the gas via an enclosed pipe from the home's lowest point to the house's highest point. Figure 1.3 is an example of a cutaway of a home with a RRNC passive mitigation system. The primary method to reduce radon is called passive soil depressurization. It consists of using a vent pipe run from the lowest to the highest level of a home. The vent pipe moves the gas out of the house to the atmosphere. The pipe at the lowest level starts under the foundation and uses a membrane barrier which is put down before the cement foundation is poured. The systems are built with the ability to attach a fan after initial home construction is complete. The installation of a fan converts the system from a passive to active; the fan substantially increases the ability of the system to eliminate radon by actively drawing the gas up through the vent pipe rather than relying on the natural rise of the gas. The use of passive systems has been shown to reduce radon levels by 50% ⁴⁴. A 50% reduction may be adequate to protect most homeowners, however if radon levels are high enough, conversion of passive to active systems may be needed. The only way to determine if a

passive system needs to be converted to an active system is by testing the home after the passive system is installed.

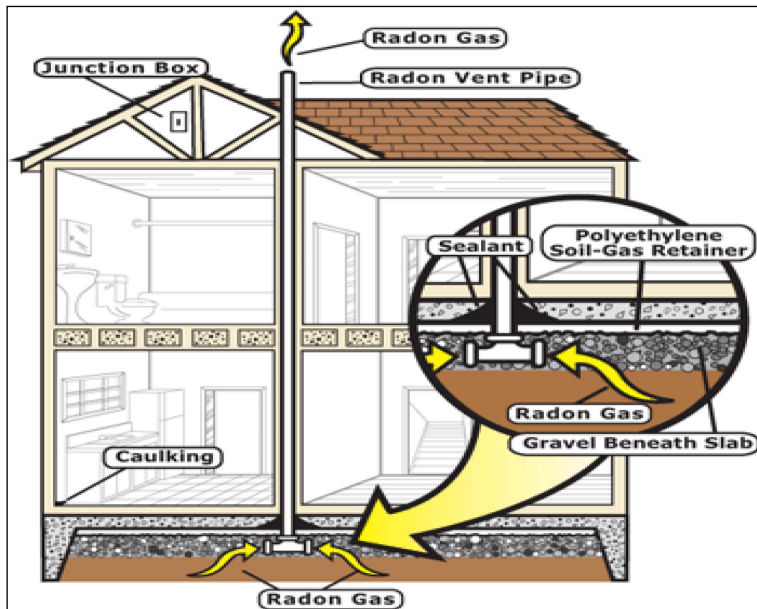


Figure 1.3 Cutaway of a Single-Family Home built with a Radon Mitigation System
Downloaded from EPA RRNC Builders: Basic Techniques on 08/25/15
http://www.epa.gov/radon/rrnc/basic_techniques_builder.html

Spitz⁴⁵ estimated that the prevention of 10% of annual lung cancer deaths would save about 16,000 lives. Steck found that the cost to have a properly working radon reduction system is a nominal cost compared to the reduction in risk and mitigation of radon in homes located in the Upper Midwest, showing that the radon reduction system had very high cost effectiveness⁴⁶. Not only would RRNC mitigation save lives, but the cost to the general public would be much less than the costs associated with the medical treatments needed to treat lung cancer. Steck concluded that mitigation would be an effective public health measure⁴⁶. To install a radon reduction system after a home is built, known as radon remediation, is costlier. Expressed in terms of quality-adjusted life years (QALY), Gray et al in 2009 found that remediation would be about ten times more expensive than RRNC mitigation^{47,48}.

RRNC versus Remediation

Radon reduction systems reduce a person's exposure to inhaled radon gas which reduces the person's risk of developing lung cancer. These systems can be installed into older homes (in a process known as remediation) or installed into new builds (RRNC). When installed as part of RRNC, systems are passive types with the ability to convert to an active system by installing a vent fan⁴⁹. When installed as part of new construction, the cost of adding radon reduction system to a home is cheaper and less obtrusive and provides homeowners reduced radon exposure for the life of the home.

Improper installation of the radon reduction systems lessens the ability of the system to remove radon gas, however in the 20 plus years that these types of systems have been installed into homes, the number of deficiencies has decreased as home builders get more experience installing these systems.⁴⁴

Radon Reduction Laws Regulations and Policies

The Federal Indoor Radon Abatement Act was passed in 1988. This Act does not give the EPA the authority to directly regulate radon in homes, nor set acceptable indoor radon concentrations. However, the Act did give the EPA the authority to provide guidelines on action levels. The Act calls for the testing of all homes and recommends the remediation of all homes that have radon concentrations of 4 pCi/L and above³⁶. The 4 pCi/L is not a health based standard because even low-level exposure to radon can put people at risk for cancer. The Act also called for the creation of new or alteration of existing construction standards, development of a citizen's guide, and carrying out radon surveys and helping to establish state programs. The long-term goal of the Act was to have indoor air as radon-free as ambient air outside the house. The rules for testing,

installing radon reduction systems, and requiring radon resistant new construction also vary from jurisdiction to jurisdiction across the United States. At this time, nine states have adopted RRNC into their statewide building codes: Connecticut, New Jersey, Washington, Michigan, Minnesota, Maryland, Oregon, Illinois and Massachusetts. How these states apply RRNC differs: in several of the states, RRNC applies only in identified high radon concentration zones, while in others, RRNC is based on home type such as one- and two-family homes. While not adopting statewide RRNC, several states identify the RRNC standard and if a local municipality decides to adopt RRNC, this is the standard they must use. Maine is the only state to adopt a RRNC standard that requires post installation testing to determine if conversion from passive to an active system is needed. However, the standard only goes into effect if the homeowner wants to build their home RRNC.

States have enacted non-building code policies that address radon risk reduction. For example, many states have laws that require disclosure of known radon levels or provision of other radon information as part of the real estate transaction. There are also laws that cover the licensing and certification of radon professionals such as such as individuals who test or mitigate homes for residential radon ⁵⁰.

According to a 2010 builder annual survey, only about 17% of new homes in the United States were constructed with RRNC. Most of these homes were in EPA-identified high radon zones (areas in the US that the EPA have identified as being more at risk for having higher concentrations of radon gas). Jurisdictions can choose to adopt a regulation or a standard from several organizations. These include Appendix F from the International Code Council (ICC), the RRNC 2.0 Standard CCAH-2013 from the

American Association of Radon Scientists and Technologists (AARST) American National Standards Institute (ANSI) and the ASTM-E1465-8 (for low rise buildings) from the American Society for Testing and Materials ^{51,52}. These standards all share the same basic elements of passive soil depressurization with the ability to be easily converted to active soil depressurization by the addition of a fan.

The principle difference between Appendix F and the other two standards is the requirement in the latter of post installation testing before the system can be certified for home occupancy. If the residential radon levels are above the national action standard set by the EPA ⁴³ of >4pCi/L, the radon reduction system must be converted from the passive system to the active system. Appendix F is a voluntary consensus standard, basically providing the minimum requirements for building a home with RRNC features in areas identified as Zone 1 (high radon concentrations). In addition, even if jurisdictions have adopted ICC into their building code, the jurisdiction has to explicitly adopt Appendix F.

RRNC 2.0 is a “model” code that jurisdictions can adopt into their own building codes. Model building codes are ones that are developed by independent standards organization that are then adopted by jurisdictions with or without modifications. Until the jurisdiction adopts the model code, it is not legally enforceable. Because this type of standard has specific requirements and not minimum requirements, there is the potential for more standardization among the different jurisdiction that adopt this standard.

The Radon Certification Act (63 P.S. §2001 et seq.) requires certification of individuals who perform “radon testing, radon mitigation and/or laboratory analysis in Pennsylvania ⁵³.” The only exception in the law is for a homeowner who is performing

his or her own radon tests. The same act requires mandatory reporting of radon test results and mitigation reports to the Pennsylvania Department of Environmental Protection. The regulations developed to enforce this act are found in Title 25 of the Pennsylvania Code Chapter 240⁵⁴. The Pennsylvania Department of Environmental Protection provides a searchable database to the public of the average residential radon test levels by zip codes. The online resource can be found at <http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Radon/RadonZip>. When the reader goes to the link, they can enter a Pennsylvania zip code to find the average and maximum radon concentrations and number of tests performed of radon measurements of the basement and first floor in that zip code. The results also give the overall average radon concentration from the database for all the basements and the first floor in Pennsylvania. According to a search performed on the site on 07/03/2019 for zip code 19518, assuming closed home conditions, the average radon concentration for basements in all Pennsylvania is 7.1 pCi/L based on the database measurements. These results are based on short term radon tests collected from 01/1990 to 12/2016. In zip code 19518 Douglassville, which includes Amity Township, the average radon concentration in basements based on 2280 tests was 6.8 pCi/L with a maximum level of 452.5 pCi/L⁵⁵. While the average radon level in this zip code is below the average radon level in Pennsylvania, all the average values in Berks County are above 4.0 pCi/L (Table1.1).

RRNC is not a statewide requirement in Pennsylvania, though several townships in the state do require it. Since 2004, Amity Township has required RRNC for all new homes built⁵⁶. According to Pennsylvania's Radon Mitigation Standards law, if a

mitigation system is activated, the system, must be “measured for effectiveness” by a short-term radon measurement no sooner than 24 hours, nor later than 30 days, following activation ⁵⁷. Testing is not required after the installation of a radon resistant system ^{58,59}.

Table I.1 Berks County Radon Test Data by Zip Code- Basement Measurements Only

City	Zip Code	Num of Tests	Max Result pCi/L	Avg Result pCi/L
Birdsboro	<u>19508</u>	657	62.8	4.6
Topton	<u>19562</u>	82	32.5	4.7
Reading	<u>19604</u>	209	33.1	5.8
New Berlinville	<u>19545</u>	30	16.8	5.8
Bally	<u>19503</u>	73	39.1	5.9
Reading	<u>19611</u>	235	42.9	6.1
Douglasville	<u>19518</u>	1018	153.2	6.4
Morgantown	<u>19543</u>	418	147.5	6.8
Reading	<u>19607</u>	895	240.0	8.1
Reading	<u>19602</u>	95	99.2	8.3
Reading	<u>19601</u>	221	197.0	8.5
Mohnton	<u>19540</u>	574	203.2	8.5
Reading	<u>19610</u>	1375	234.0	8.9
Reading	<u>19606</u>	1696	467.0	9.0
Bechtelsville	<u>19505</u>	175	80.6	9.2
Blandon	<u>19510</u>	628	81.7	10.2
Boyertown	<u>19512</u>	1041	616.0	11.0
Barto	<u>19504</u>	347	164.6	11.1
Reading	<u>19608</u>	1389	334.9	11.4
Reading	<u>19609</u>	463	239.6	12.3
Wernersville	<u>19565</u>	390	158.0	12.6
Fleetwood	<u>19522</u>	816	1204.7	12.8
Reading	<u>19605</u>	671	1305.0	13.4
Temple	<u>19560</u>	186	166.0	13.5
Oley	<u>19547</u>	245	148.0	13.6
Bethel	<u>19507</u>	54	147.2	13.9
Mertztown	<u>19539</u>	211	313.0	14.3
Womelsdorf	<u>19567</u>	90	63.0	14.4
Hamburg	<u>19526</u>	363	133.5	15.1
Kutztown	<u>19530</u>	404	221.4	16.2
Leesport	<u>19533</u>	363	320.9	17.0
Robesonia	<u>19551</u>	178	173.9	17.1
Shoemakersville	<u>19555</u>	75	179.0	18.0
Bernville	<u>19506</u>	408	215.9	20.2
Kempton	<u>19529</u>	165	444.5	22.0
Mohrsville	<u>19541</u>	208	187.9	22.8

Lenhartsville	19534	80	170.8	23.4
Hereford	18056	Insufficient Data *	Insufficient Data	Insufficient Data
Bowers	19511	Insufficient Data	Insufficient Data	Insufficient Data
Centerport	19516	Insufficient Data	Insufficient Data	Insufficient Data
Earlville	19519	Insufficient Data	Insufficient Data	Insufficient Data
Geigertown	19523	Insufficient Data	Insufficient Data	Insufficient Data
Linekiln	19535	Insufficient Data	Insufficient Data	Insufficient Data
Lyon Station	19536	Insufficient Data	Insufficient Data	Insufficient Data
Maxatawny	19538	Insufficient Data	Insufficient Data	Insufficient Data
Monocacy Station	19542	Insufficient Data	Insufficient Data	Insufficient Data
Mount Aetna	19544	Insufficient Data	Insufficient Data	Insufficient Data
Pine Forge	19548	Insufficient Data	Insufficient Data	Insufficient Data
Rehrersburg	19550	Insufficient Data	Insufficient Data	Insufficient Data
Shartlesville	19554	Insufficient Data	Insufficient Data	Insufficient Data
Strausstown	19559	Insufficient Data	Insufficient Data	Insufficient Data
Virginville	19564	Insufficient Data	Insufficient Data	Insufficient Data
Reading	19603	Insufficient Data	Insufficient Data	Insufficient Data
Reading	19612	Insufficient Data	Insufficient Data	Insufficient Data
Reading	19640	Insufficient Data	Insufficient Data	Insufficient Data

From the Pennsylvania Department of Environmental Protection Radon Test Data by Zip Code "For reference, the U.S. EPA has established their action level at 4.0 pCi/L, and they have estimated that the national average indoor radon concentration at 1.3 pCi/L. The average indoor concentration in Pennsylvania basements is about 7.1 pCi/L, and 3.6 pCi/L on the first floor. Data Qualifications: Data as supplied to the Department from the certified radon laboratory and testing community. All short-term test methods, dates from 1/1/1990 to 12/31/2011, house types; 2-story, 3-story, ranch, split level, bi-level, cape cod, raised ranch, and contemporary. This data represents radon concentration measurements conducted under "closed-house" conditions. This type of data would in general show higher results compared to a measurement made over an entire year, under "normal living" conditions. We report the "closed-house" condition testing results because they represent the vast majority of testing conducted in the Commonwealth.

Note: The reported average more closely approaches the true population average as the sample size increases. This is one reason why we do not report an average when there are fewer than 30 test results for a given zip code."

*Insufficient Data- indicates that averages not reported for cities/zip codes with fewer than 30 test results.

Amity Township, PA Selection of Jurisdictional and Additional Health Data

Amity Township, located in Berks County, Pennsylvania, adopted Appendix F "Radon Control Methods" Ordinance 202A on June 28th, 2004. The ordinance became effective on January 01, 2005. All new one or two family homes built in Amity Township after January 01, 2005 should, according to law, be built with radon resistant new construction techniques⁵⁶. These RRNC homes were required to be built with

passive subslab depressurization systems⁵⁹. Amity township does not require the measurements of a home's radon levels before or after a passive radon reduction system is put into a home⁵⁹. The Pennsylvania Department of Environmental Protection recommends RRNC homes be tested after a family has moved in, to determine if the system needs to be converted from a passive system to an active system. In addition they also recommend that a home be tested every two years if a non RRNC home was mitigated, however these are recommendations and not requirements⁶⁰.

The township regulations also require permits whenever a vent pipe and an electrical junction box are installed in a new or renovated home. According to Amity Township's Code Enforcement officer, a permit is not required when a passive radon resistant system is converted to an active system⁵⁹. The permits will be used to identify the homes built with passive radon reduction system after mandatory RRNC went into effect.

To assess the impact of RRNC on radon levels in homes without remediation the geometric mean radon concentration of these RRNC homes will be compared to geometric mean from non RRNC non-remediated homes in Amity. The non RRNC (non-remediated) homes in Amity mean value will be used to represent the expected mean residential radon concentration. We will also compare the average radon concentration expected for indoor homes based on state radon program (if possible.) Also, the geometric mean of radon concentration of homes the RRNC homes will be compared when going from a passive system to active system. We will seek to demonstrate the reduction in radon concentrations that homeowners will be exposed to, going from no systems, to homes with passive systems, and then to homes with active systems. By

using an established lung cancer radon risk model, we will then show the reduction in lung cancer risk due to homes being built with RRNC.

We will also determine the percentage of smokers in Pennsylvania using data from Behavioral Health Risks of Pennsylvanian Adults study (BHRPA). Data is collected annually by the Pennsylvania Department of Health, Bureau of Health Statistics and Research in a publicly available database on modifiable risks that affect people's health. Using already established risk models, we will be able to determine the risk of lung cancer due to the exposure to combined risk factors.

The study will evaluate the reduction in risk for developing lung cancer in homes with RRNC (both passive and active systems), compared to the risk of lung cancer in homes that have not been remediated using subslab depressurization.

We will be able to show that, based on the reduction seen in Amity, we could estimate the lung cancer risk reduction if additional townships adopt RRNC.

When the radon measurements of Amity Township were plotted in a histogram, they showed a non-normal distribution with a right-hand tail. When the distribution is log transformed, the values show a log normal distribution. This is because most of the values are close to zero with the results being skewed due to the few homes that have very high residential radon concentrations. This is consistent with other residential radon distributions, such as the one done by the EPA ³⁶. According to the EPA, the average (arithmetic) residential radon concentration in the United States is 1.3pCi/L ⁴³. As previously stated, according to the Pennsylvania Department of the Environment (PA DEP), the average basement radon concentration was 6.4 pCi/L with a maximum level of 153.2 pCi/L. According to PA DEP Radon Zip, the average indoor concentration in

Pennsylvania basements is about 7.1 pCi/L. Analysis of residential radon measurements collected by PA DEP, Casey et al., 2015 determined that the median basement home radon concentration levels is 3.2 pCi/L (118.4 Bq/m³)⁶¹.

Radon lung cancer risk models

Cancer risk models have been developed to describe specific cancer risk from exposure to different radiation concentrations¹¹. Absolute risk is the probability or chance that an event, such as death, will occur after a defined exposure. Absolute risk cancer prediction models are utilized to determine an individual's or population's chance of developing cancer over time after an environmental exposure and other risk factors. The risk factors can include intrinsic ones such age, gender, race, health history, smoking status, economic status and time since exposure¹¹. Once developed, the models are tools that can be used to assess how policies can help protect public health by reducing lung cancer risk. Several models have been developed including BEIR VI, Darby, Krewski and IRCP^{4,7,22,35}. Many factors are to be considered when creating a model to estimate the risk of developing lung cancer from exposure to residential radon gas. These factors include exposure, dose, effective dose, and dose response. Exposure (how much of the radon gas is actually inhaled) includes the length of the exposure, the concentration of radon gas, and the individual's respiratory rate at the time of the exposure. The effective dose is how much stays within the person to potentially cause an effect. Finally, the dose response is how the body responds to the effective dose, and is influenced by how often the person was exposed, at what age was the exposure, their gender, smoking habits (ever smoked or never smoked), and overall health⁴.

The BEIR VI models were based on cohort studies of miners, while the Darby and Krewski models were based on case control studies of residential radon concentration and cancer rates. In cohort studies, the relative risk is determined based on the risk of developing disease after a person has been exposed to the toxicant. In case-control studies, individuals with disease (cases) are compared to similar individuals without disease (controls) to determine the odds ratio. The odds ratio is the proportion of exposed individuals with disease divided by those exposed individuals without disease⁶². Under certain conditions, such as when the outcome is rare, the odds ratios can be used to approximate the relative risk⁶³.

The models can express risk for the population as either excess relative risk (ERR) or excess absolute risk (EAR). Both are cancer risks relative to the populations' background cancer risk. The ERR is the proportional increase of risk above background absolute risk while EAR is additional risk above background absolute risk. The ERR is a good way to measure the strength of an association between an exposure and incidence of disease, while the EAR is a measure of how much of the disease is due to an exposure. Additionally the ERR may better measure a person's radon lung cancer risk when they have additional risk factors such as smoking¹¹. The ERR of lung cancer due to radon exposure is much higher for non-smokers, however the EAR is higher for smokers due to their higher baseline risk for lung cancer¹⁴. Lifetime relative risk (LRR) is another way to express risk. It is the ratio of lung cancer risk due to radon exposure versus the lung cancer risk due to background exposure (R_e/R_o).

The BEIR VI radon lung cancer risk models were developed using data from epidemiological studies on male adult miners. The models were not created to estimate

how much radiation the lung receives (dosimetric). To extrapolate from a group of miners to a residential population, certain assumptions were used. Underground miners were exposed to higher concentrations of radon particles for shorter periods versus residential radon exposure. Underground miners as a population group typically consisted of adult males in generally good health, while the residential population will consist of individuals of all ages, gender and health. Additionally, the underground miners' respiratory rates during the exposure would be higher due to physical exertion, compared to residential exposures^{4,10}. Consequently, the miners are not only breathing in air with higher levels of radon but are breathing it in at a higher rate. Conversely the slower respiratory rate of residential population could also be a risk, allowing the radioactive particles to reside longer in the bronchial tube, thereby potentially giving more time for the radioactive particle to hit the cells, attach to lung tissue, and cause cellular damage. Because of these differences, extrapolation from the one population (male underground mine workers) to the general public must be done carefully and with adjustments to account for the differences in population characteristics.

The NAS/BEIR VI committee developed two models to determine the ERR of lung cancer from radon exposure above the populations background risk of lung cancer. The two models are identical except for the exposure rate adjustment factor γ_z . In one model, the rate of exposure would be determined from the exposure age concentration- γ_{con} (average concentration of radon during time of exposure.) In the second model, the rate of exposure would be exposure across ages, duration- γ_{dur} (time period of exposure) See Figure 1.4.

Population radon exposure data was then used with the models to estimate the potential lung cancer risk due to these radon exposures. Excess relative risk of lung cancer due to radon exposure is a linear function of cumulative exposure and varies due to time, time since exposure, age, and either exposure age concentration or exposure age duration. The model was built from the data provided by joint analysis of the studies of 11 cohorts of miners ³³.

BEIR VI, using the models they developed and data from the EPA's National Radon Residential Survey, concluded that with home radon concentration levels reduced to 4 pCi/L, 3 to 4 % of total lung cancers would be prevented (about one third of the radon induced lung cancers ⁴.

$$ERR = \beta (w_{5-14} + \theta_{15-24} w_{15-24} + \theta_{25+} w_{25+}) \phi_{age} \gamma_{z^*}$$

Depending on which model used γ_{z^*} is either γ_{con} or γ_{dur}

Figure 1.4 National Research Council (NCR) BEIR VI ERR Model 1999

The EPA modified the two BEIR VI risk models and combined them into a single model ¹⁴. The estimates of this model would be the average of the estimates of the two BEIR models ⁶⁴. W^* combines the BEIR VI time since exposure into a single age-weighted exposure time. The exposure to radon lung cancer risk relationship (β) is equal to 0.0634 ⁶⁵.

$$e(a) = \beta W^* \Phi_{age}(a)$$

Figure 1.5 The EPA model for ERR

The estimated relative risk (ERR) for lung cancer due to radon exposure is double in individuals who have ever smoked versus those who never smoked on average. The combined risk for lung cancer from smoking and radon exposure is sub-multiplicative. The larger risk factor is cigarette smoking. Both models assume a linear model with no threshold dose (a single alpha particle can cause tissue damage.) There is some evidence

that radon also shows inverse dose rate effect (protraction enhancement) at lower doses. That is, more damage can occur in those exposed to the same total dose that is broken into lower multiple chronic exposures versus a single acute dose.

However, in a paper by Lubin et al., the protraction enhancement would diminish at the very low dose such as those found in residential setting, due to the low probability of an alpha particle hitting a cell and causing damage⁶⁶. This in turn would reduce the chances of a cell getting multiple hits. Also, at a certain point of exposure to higher radon concentration, the exposed cells may be killed before becoming cancerous and regardless of increased concentration there is less of an effect to be seen. Both the BEIR VI and the EPA models express the risk of lung cancer due to radon exposure as lifetime attributable risk (LAR). LAR would be the early death due to lung cancer from residential radon exposure. The Darby model, like the BEIR VI model, applies a dose response relationship that is also linear: the lung cancer risk increases with increasing residential radon exposure. Darby and colleagues calculated that lung cancer risk increases by 8.4% for every 100 Becquerels per cubic meter (Bq/m³). The model is based on joint analysis of 13 European residential case-control studies⁶⁷.

$$\text{ERR} = (\beta)(X)$$

Figure 1.6 Darby Model for ERR, 2005

Where β is the slope parameter of the exposure–response relation, and X is the mean radon concentration in the homes inhabited during the 5- to 34-year period before study enrollment. The model they developed also used a linear relationship to estimate relative risk at the residentially observed radon dose. Other models such as log-linear or linear-quadratic did not fit the data any better. The equation for the fitted model with a linear relationship is $RR = 1 + 0.00084\chi$, where χ is the measured radon level with 95%

confidence limits. The relative risk is equal to 1 at 0 Bq/m³, i.e., no additional risk.

Krewski, et al. did a similar pooled analysis, but of 7 North American residential case-control studies, they found that relative risk increased by about 10% per 100 Bq/m³ ²².

While the absolute risk of lung cancer due to indoor radon is much higher for smokers because their baseline risk is higher, the European pooled analysis found no evidence that excess relative risk of lung cancer (that is the relative proportion of the risk due to indoor radon exposure) varied with age, sex, or smoking history ⁶⁷. While there was a large number of residential data in the sample set used, it was still less than the underground miner data studied.

The residential model utilized here assumes the risk is the same for males and females, and for individuals of all ages and health. The model is also able to estimate the risk of lung cancer from radon exposure and smoking, by comparing two groups: people who have ever smoked and never smoked ²².

While all the peer reviewed excess relative risk (ERR) models we considered to determine the lung cancer due to radon exposure include a smoking interaction, the interaction depends on the model. All the models are consistent in showing increased risk of lung cancer from exposure to residential radon, and all are linear non-threshold models. How the smoking interaction is handled by the Darby model makes it a better fit for analyzing the data utilized in this research (Table 1.2). The data collected is a snapshot of Amity Township, PA population's exposure to the known hazard of radon. We were able to characterize the smoking status into current, former and never smokers at the county level (Berks County, PA). By applying the Darby model, it is possible to factor in these two categories of smokers, rather than a single ever-smoked category

utilized in some of the other models. This is important, since former smokers are at higher risk than never smokers, but their risks compared to current smokers drop the longer they are former smokers.

Table 1.2 Summary of Smoking Status Variables in Various Lung Cancer Risk Models

	Ever Smoked	Current	Ex-smoker	Never Smoked
BEIR VI	Yes	No	No	Yes
Krewski	Yes	No	No	Yes
Darby	No	Yes	Yes	Yes
Amity Township Data	No	Yes	Yes	Yes

Phase II Assessing the Lung Cancer Risk from both RRNC and Non-RRNC Homes

Phase II assesses the lung cancer risk due to residential radon exposure. In this phase, additional information to determine the risk will be identified and obtained.

Stage 1: Obtaining Additional Publicly Available Information

To supplement the residential radon measurements additional information is needed to assess the lung cancer risk reduction associated with adoption of RRNC. The additional supportive data includes lung cancer incidence and mortality rates at local, state and national levels. This data provides background understanding of lung cancer risks and context for the proposed risk modeling. In Pennsylvania, incidence and mortality rates can be obtained at both the State and County levels from the Pennsylvania Department of Health. At the township level, the Department of Health only provides either the actual number of deaths or new cases of lung cancer^{68,69}. The townships’ incidence and mortality counts will be used to calculate Amity Township’s lung cancer incidence and mortality rates. For these rates to be consistent with the County and States rates, the same standard population will be utilized, which in this case was the 2000 US standard population. The age group populations for Amity Township from 2010 to 2015

were obtained from American FactFinder, a website created and maintained by the US Census Bureau. The townships age group populations were estimated numbers using the 2010 census. This data will be used to compare populations in homes with and without RRNC in Amity. The incidence and mortality and smoking rates for Berks County, Pennsylvania and the United States are also presented Table 2.1 and Table 2.2.

Based on data from the Behavioral Risk Factor Surveillance System (BRFSS) of adults 18 year and older, smoking status was obtained and is shown in Table 2.3. The table divides the population into individuals who are current smokers, former smokers and those who never smoked. The survey was conducted by phone (surveys from 2011 and after included cell phones in addition to landlines.) Presenting the data at different levels (State, County, and Township) shows trends in data from Amity Township as it compares to other populations. An additional benefit of presenting the data in this form is that it also prepares for later comparison with other townships in Pennsylvania that have adopted RRNC.

Table 1.3 Invasive Lung Cancer Incidence Age Adjusted Rate per 100,000*

Year	Amity Township, PA	Berks County, PA	PA	USA
2009-2013	66.12	63.8	65.8	62.52
2008-2012	70.68	62.8	66.8	64.1
2007-2011	67.94	61.3	68.2	65.44
2006-2010	63.24	64.2	69	66.74
2005-2009	62.52	66.2	69.9	67.94
2004-2008	58.18	64.6	69.8	68.62

* "These data were provided by the Pennsylvania Department of Health. The Department specifically disclaims responsibility for any analyses, interpretations, or conclusions"

Table 1.4 Invasive Lung Cancer Mortality Age Adjusted Rate per 100,000*

Year	Amity Township, PA	Berks County, PA	PA	USA
2009-2013	52.9	42.3	47.4	46
2008-2012	55.32	43.1	48.7	47.3
2007-2011	49.44	43.6	49.9	48.4
2006-2010	42.62	45.4	51	49.6
2005-2009	33.6	46.4	52	50.66
2004-2008	35.98	47.6	52.7	51.66

* "These data were provided by the Pennsylvania Department of Health. The Department specifically disclaims responsibility for any analyses, interpretations, or conclusions"

Table 1.5 Smoking Prevalence (% of the population) in the United States, Pennsylvania and Berks County, PA*

Year	Berks County, PA			Pennsylvania			United States		
	Current	Former	Never	Current	Former	Never	Current	Former	Never
2013-2015	23	26	51	20	26	54	17	21	62
2012-2104	23	28	50	21	25	54	18	21	62
2011-2013	21	26	52	22	26	53	18	21	61
2010-2012	19	26	54	18	26	56	19	21	60
2009-2011	20	27	53	19	26	55	20	21	59
2008-2010	22	26	52	20	26	54	20	21	59
2007-2009	23	26	51	21	25	54	20	21	58

*Based on data from the Behavioral Risk Factor Surveillance System (BRFSS), Prevalence and Trends Data for Pennsylvania. "These data were provided by the Pennsylvania Department of Health. The Department specifically disclaims responsibility for any analyses, interpretations, or conclusions"

Stage 2: Risk Assessment

Research Design/ Methodology

Hypothesis

On an individual basis, those living in homes built with Radon-Resistant New Construction (RRNC) will be exposed to lower concentrations of radon gas and be at lower risk for developing lung cancer than those living in homes without RRNC. To determine how much the population risk will be reduced, residential radon exposure risks will be compared in Amity homes built with and without RRNC.

Specific Aims and Objectives

Aim 1: Demonstrate that townships in Pennsylvania that have adopted RRNC will have a simple but effective method to reduce residential radon concentration. The less radon to which a homeowner and their family is exposed, the lower the risk of lung cancer incidence and mortality due to radon exposure.

This aim will be achieved by characterizing the residential home radon levels in homes in Amity Township, Berks County, Pennsylvania before and after adoption of RRNC in 2004.

To test the hypothesis that persons living in homes in Amity Township built after 2004 (after the adoption of RRNC) will have reduced lung cancer risk requires determining the residential radon concentrations in Amity Township. The Pennsylvania Department of Environmental Protection (PADEP) maintains a database of measurements from residential radon tests from all 67 counties submitted by certified testers, laboratories, or homeowners⁶¹. Test results are submitted to PADEP via the GreenPort website at <http://www.depgreenport.state.pa.us>. In addition to the radon measurements, PADEP requires information such as the address, zip code, building type, test start and end date, type of test and results⁶⁰. All the home measurements went through a geocoding process to determine the homes' latitude and longitude. The researchers used ArcGIS 10 and multiple maps in the process⁶¹. Geocoded data gives the ability to study the data with other spatial data. The measurements will be based on the home addresses; no personal information of the residents was identified or needed for this study.

An initial subset of homes was pulled from the larger data set based on latitude and longitude coordinates to identify a rectangle that would contain homes within Amity Township, PA. Geographic Information System (GIS) was then used to make the final selection of homes located within Amity Township. All RRNC homes in Amity Township require a permit for the radon reduction piping and electrical outlet receptacle before being built; the permits are kept in a computerized database and were obtained from an open records request (Loomis, 2014 personal communication ⁵⁸). Based on permit data over the period starting in January 01, 2005 (enactment of RRNC) through December 31, 2014, homes within Amity Township will then be divided between non-RRNC homes and RRNC homes. Only the basement measurements will be used in these analyses.

Many of the homes measurements in the PADEP data contained multiple results. Multiple measurements from a single location taken on the same day or within 48 hours will be averaged together and counted as a single measurement. For homes measured on multiple occasions (more than 48 hours apart), an oldest and newest measurement will be used (to help identify homes that potentially have been remediated in non-RRNC homes or converted from passive to active in RRNC homes.) Descriptive statistics will be utilized to summarize and characterize radon levels in the Amity Township homes data set.

Aim 2: Determine the population risk lung cancer risk reduction for the residential population living in homes built with RRNC. The public health benefits of a lung cancer risk reduction to both the individuals and populations would be significant. Prevention of

as little as 1% of the annual lung cancer deaths would save more than 1600 lives in the United States ¹⁴.

The reduction in risk will be determined mathematically by using the average arithmetic radon concentrations (from homes with and without RRNC) and already developed models to compare the lung cancer risk. While there are several lung cancer risk models for radon exposure, the model utilized will be the one that best fits the available data.

Three of the models considered for this analysis were Darby and Krewski (both based on residential data), and the Environmental Protection Agency (EPA) model which combines the two models developed by NRC (BEIR IV) and were based on data from studies of underground miners. ^{4,7,14,22}. After reviewing the models and available data, it was determined that risk will be calculated using the Darby model. This model determines the relative risk for lung cancer based on residential radon exposure and takes into consideration smoking habits by dividing the population into current, former, and lifelong never smoked. In addition to fitting the smoking population, the model was also chosen for its simplicity of being a slope line intercept. Smoking habits will affect a person's background risk for developing lung cancer. Smokers have a higher background risk versus non-smokers for developing lung cancer.

Phase III – Risk Management (Decision Phase)

In this phase, the benefits and costs are reviewed using the different approaches taken to reduce residential radon exposure. What are the estimated health and economic benefits of adopting a RRNC building standard, including which standard to adopt, when it comes to lung cancer? In this phase, the benefits and costs of different options will be

reviewed for their risk-reduction potential (the health and economic benefits of adopting RRNC when it comes to lung cancer).

Hypothesis

Requiring homes to be built with RRNC is an effective health policy and cost-effective public health policy approach to reduce the lung cancer risk due to exposure to residential radon.

Specific Aim and Objective

Aim 3: Using cost-benefit analysis, demonstrate that adoption of RRNC as the standard for all new home construction in additional Pennsylvania Townships or Statewide would be a cost-effective public health intervention to reduce lung cancer risk from radon exposure in homes.

Applying cost-benefit analysis with the use of a decision tree is an integral part of phase III. The decision tree is a structured way to estimate the risk and rewards of adopting RRNC by quantifying different outcomes. In this situation, the outcome is the total cost of lung cancer. The decision tree shows that applying and paying upfront for the RRNC radon prevention measure is more cost effective than paying later for preventable total cancer costs. A simple decision tree is shown in Figure 1.7. The outcomes costs are determined based on the probability of getting cancer for individuals living in homes with and without RRNC determined by utilizing a residential radon risk model and Amity Township, PA residential radon concentrations. The values are negatives to indicate that these are monetary resources that will be spent (in the future.)

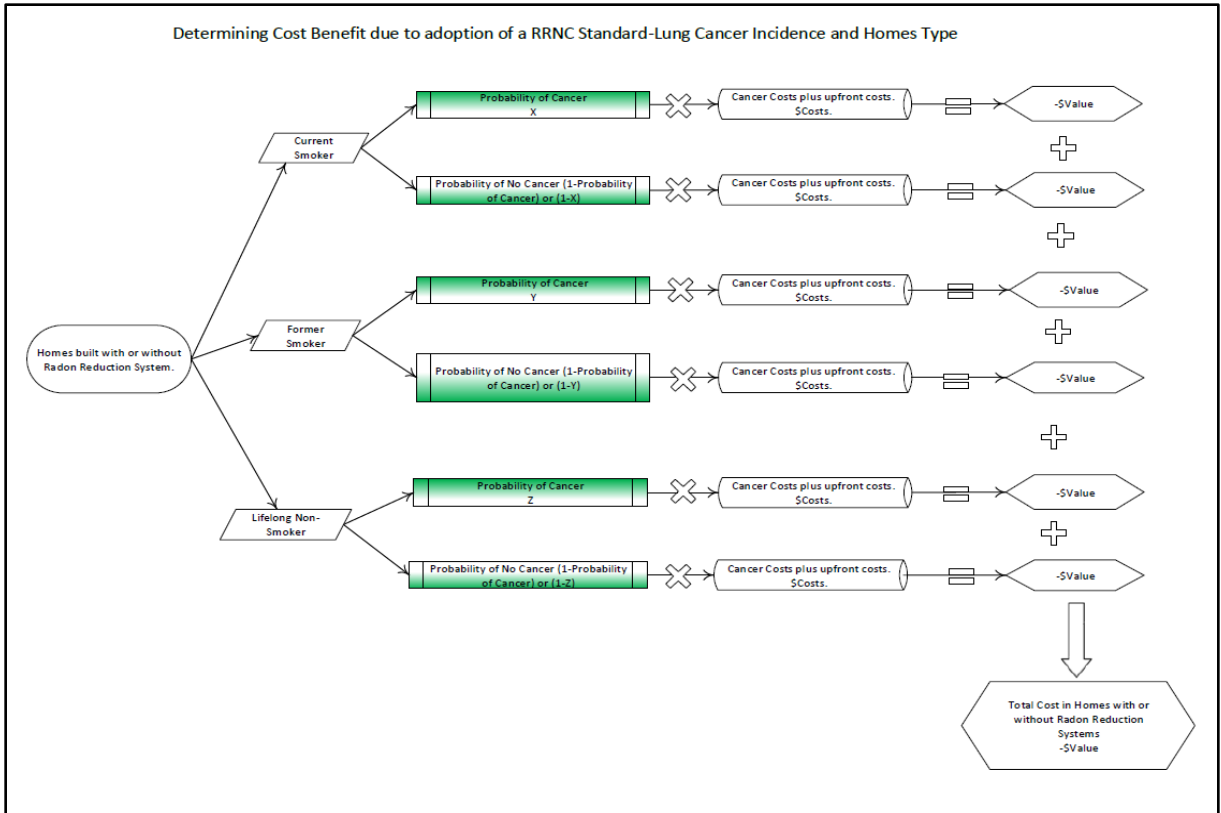


Figure 1.7 Simple RRNC Lung Cancer Decision Tree

Specific information was needed to model the potential benefits associated with RRNC. These included the cost of building a home with RRNC and the total cost of illness and death from lung cancer. The probability of Amity Township residents getting cancer and then dying from cancer was determined based on smoking status (current, former and never) and residential radon exposure (RRNC and Non-RRNC.) The Darby relative risk methodology of lung cancer from residential radon exposure was used to determine the probability.

Aim 4: Determine if adoption of a specific RRNC standard would maximize the health benefit received when building homes with RRNC. All the RRNC standards require new home construction be built with passive radon reduction systems. These systems have the ability to be easily converted from passive to active by the addition of a fan. There are differences between passive and active systems. One key difference is the

requirement for post installation preoccupancy radon concentration testing. The ability to test prior to occupancy can verify if the passive system has reduced the radon concentration to acceptable levels. Passive systems reduce residential radon between 30 to 70%. If the radon concentration is still too high, the system can then be converted to active. Active systems reduce residential radon 50 to 99% ⁷⁰.

Chapter 2: Manuscript 1 Adoptions of a Radon Resistant New Construction standard by Amity Township, PA as a simple but effective strategy to reduce residential radon gas exposure.

Abstract: Exposure to residential radon gas is the second-leading cause of lung cancer.

Most of the counties in Pennsylvania have been identified by the EPA as having predicted residential radon levels greater than 4 pCi/L. To reduce residential radon exposure in 2004 Amity Township, PA (in Berks County) adopted International

Residential Code (IRC) Appendix F Residential Radon New Construction Standard.

After January 1, 2005 all new homes have to be built as radon resistant new construction.

Objective: To determine if adoption of a Radon Resistant New Construction (RRNC) building code standard has reduced residential radon exposure in Amity Township, PA.

Methods: Using a database of indoor radon test results compiled by the Pennsylvania Department of Environmental Protection (PADEP) Bureau of Radiation Protection, we analyzed a subset of radon measurement identified by Geographic Information System (GIS) as belonging to single family homes in Amity Township, PA. The subset was further divided, based on permit data, to identify homes that were built after the radon resistant new construction (RRNC) appendix F building code standard went into effect (identified as RRNC) compared to homes built before mandatory RRNC (identified as non-RRNC).

Results: Radon measurements of 1,261 homes located in Amity Township, PA were investigated. Analysis of the 1,160 homes built before mandatory RRNC went into effect found that the mean radon concentration was 7.03 pCi/L (239.02 Bq/m³) and the geometric mean was 4.06 pCi/L. The mean radon concentration of RRNC homes was 5.45 pCi/L (201.65 Bq/m³) and the geometric mean 2.55 pCi/L. In general residents in homes built after the mandatory RRNC standard went into effect were exposed to 22%

lower residential radon concentrations than individuals in homes built before the standard went into effect.

Conclusion: Homes built after the RRNC standard was implemented in Amity Township, PA showed lower radon concentrations than homes built without RRNC. Future studies of existing home stock that was remediated and RRNC built homes in which the systems were converted from passive to active will add to our understanding of the effect of remediation.

Introduction

Radon 222 (^{222}Rn), a known human carcinogen, is a gas found in the soil surrounding many homes in the United States. It is formed during the natural radioactive decay of uranium in the soil. Radon can move from the soil into the home where the occupants can be exposed through inhalation. Multiple epidemiological studies have linked lung cancer to radon exposure. Epidemiological studies of underground uranium miners exposed to high concentration of radon gas have shown an increased risk of developing lung cancer^{10,13} Residential case control studies have also found that increasing exposure to radon gas increases the individual's risk for developing lung cancer^{7,10,13,22}. Residential radon has been found in homes across the entire United States; however, some homes are at higher risk for elevated radon levels. Soil that contains higher levels of light-colored volcanic rocks, granites, dark shales, sedimentary rocks that contain phosphate tend to have higher levels of uranium^{13,41}. A soil with higher uranium concentration will also have higher concentrations of the uranium decay products such as radon gas that can potentially enter the house. Amity Township, located in Berks County, Pennsylvania has soil with higher uranium content.

Home characteristics that also increase the potential for radon entering the home include cracks in the foundation, basements surrounded by earth, walls built below grade. Once inside the home, residents can breathe in the radon gas. Inhaled radon exposure is the second leading cause of lung cancer after smoking and is the leading cause of lung cancer in non-smokers.

Since the gas is due to the natural decay process of substances in the environment, the only way to prevent accumulation in a home is to build the home with techniques that restrict the gas from entering and provide a way to remove radon that does enter the home. These techniques are called radon resistant new construction (RRNC.) RRNC reduces radon levels by venting the gas via an enclosed pipe from the home's lowest point (usually under the foundation) to the house's highest point (several inches above the roof of the home). The systems are built with the ability to attach a fan after initial home construction is complete. The use of the fan converts the system from a passive to an active one by pulling gas through the vent pipe rather than relying on the natural rise of the gas.

Amity Township, located in Berks County, Pennsylvania, adopted Appendix F "Radon Control Methods" Ordinance 202A on June 28th, 2004. The ordinance became effective on January 01, 2005. All new homes built in Amity Township after January 01, 2005 were built with radon resistant new construction techniques⁵⁶. These homes were required to be built with a passive subslab depressurization systems⁵⁹. Amity township does not require the measurements of a home's radon levels before or after a passive radon reduction system⁵⁹. The Pennsylvania Department of Environmental Protection recommends RRNC homes be tested for radon after a family has moved in, to determine

if the system needs to be converted from a passive system to an active system. In addition, they also recommend that a home be tested every two years if a non-RRNC home was mitigated. It is important to note that these are suggestions; recommendations are not legal requirements⁶⁰.

To determine if adoption of a RRNC standard is an effective way to reduce residential radon concentrations, residential radon levels in Amity Township, PA were compared before and after the RRNC standard went into effect.

Methods

Study Sample

The study samples (Amity Township Residential radon measurements) were a subset of measurements from a database maintained by The Pennsylvania Department of Environmental Protection (PADEP). The database contains all the state radon measurements submitted by certified testers, laboratories, or homeowners to the state, as required by law⁶¹. (See title 25 of the Pennsylvania Code Chapter 240.303.) Additional information is included such as the address, zip code, building type, test start and end date, type of test and results⁶⁰. The database was obtained through a data sharing agreement with the Commonwealth of Pennsylvania. The database was updated to include the latitude and longitude of the testing locations⁶¹. An initial subset of homes was pulled from the larger data set based on latitude and longitude coordinates to identify a rectangle that contains homes within Amity Township, Table 2.1. Geographical Information Systems (GIS) methods were then used to make the final selection of homes that are located within Amity Township (Figure 2.1). There are an estimated 3,979 single or two-family homes in the township based on the 2015 census. After the use of GIS,

1,261 single and two-family homes in Amity Township with residential radon measurements were identified, about 32% of the total number of possible homes as indicated by the census. This is not surprising, since testing for residential radon is not mandatory except after a passive system has been converted to an active system⁵⁷. A histogram, Figure 2.2, of the radon concentrations of the 1,261 single and two-family homes shows a non-normal distribution of radon measurements (skewed with a tail.) The nature of this distribution aligns with the literature on radon distribution, which indicates that most homes have very low levels of radon gas concentration, but the results are then skewed due to a few homes having very high radon gas concentrations. The histogram also shows that 50% of the homes have residential radon concentrations below 4 pCi/L, and the skewed distribution forms a tail in which 20% of the homes have concentrations above 10 pCi/L. Less than 1% had concentrations above 50 pCi/L.

When the data is log-transformed, Figure 2.3 the data takes on the appearance of a normal distribution. Because of the data's distribution, the geometric mean will be the preferred measure of central tendency to describe the data, although the arithmetic mean is also used when comparing the data to average values used by the EPA when describing residential radon concentrations. The arithmetic and geometric mean residential radon concentrations in the one or two family in Amity Township, PA was 6.90 and 3.92 pCi/L, respectively. The mean residential radon concentration is higher than the average value for the United States and for Pennsylvania. According to the EPA, the average (arithmetic) residential radon concentration in the United States is 1.3pCi/L⁴³. PA DEP Radon Zip found that the average indoor concentration in Pennsylvania basements of all home types to be about 7.1 pCi/L, and that the average arithmetic basement radon

concentration for zip code 19518 (which includes Amity Township homes) was 6.4 pCi/L with maximum level of 153.2 pCi/L (Table 1.) Casey et al., 2015 determined a much lower median basement home radon concentration levels of 3.2 pCi/L (118.4 Bq/m³)⁶¹.

Table 2.1 Amity Township, PA Rectangle by Latitude and Longitude

Latitude	40.2370 to 40.36039
Longitude	-75.62405 to -75.87467

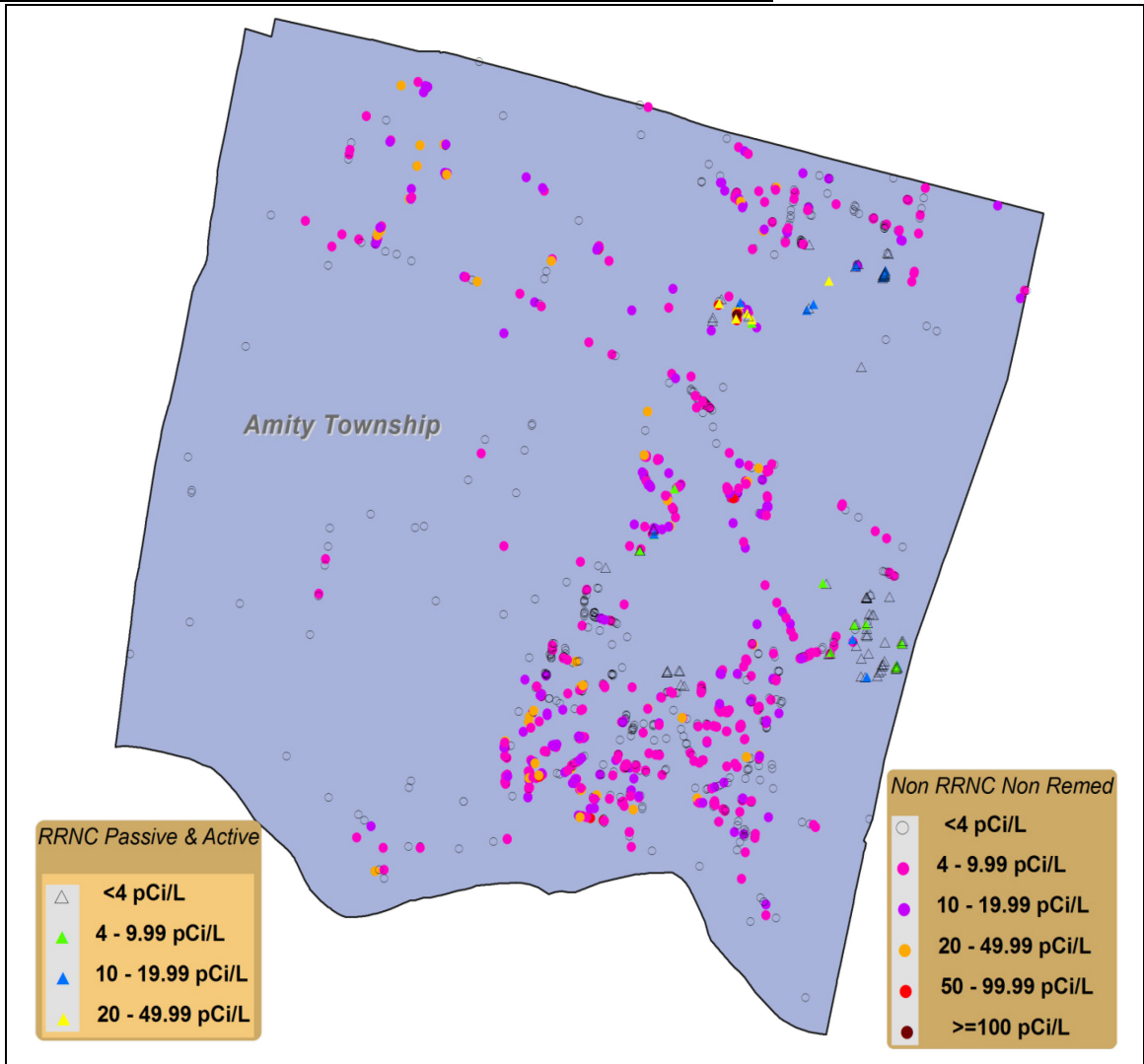


Figure 2.1 Radon Concentration of homes in Amity Township, PA identified by GIS.

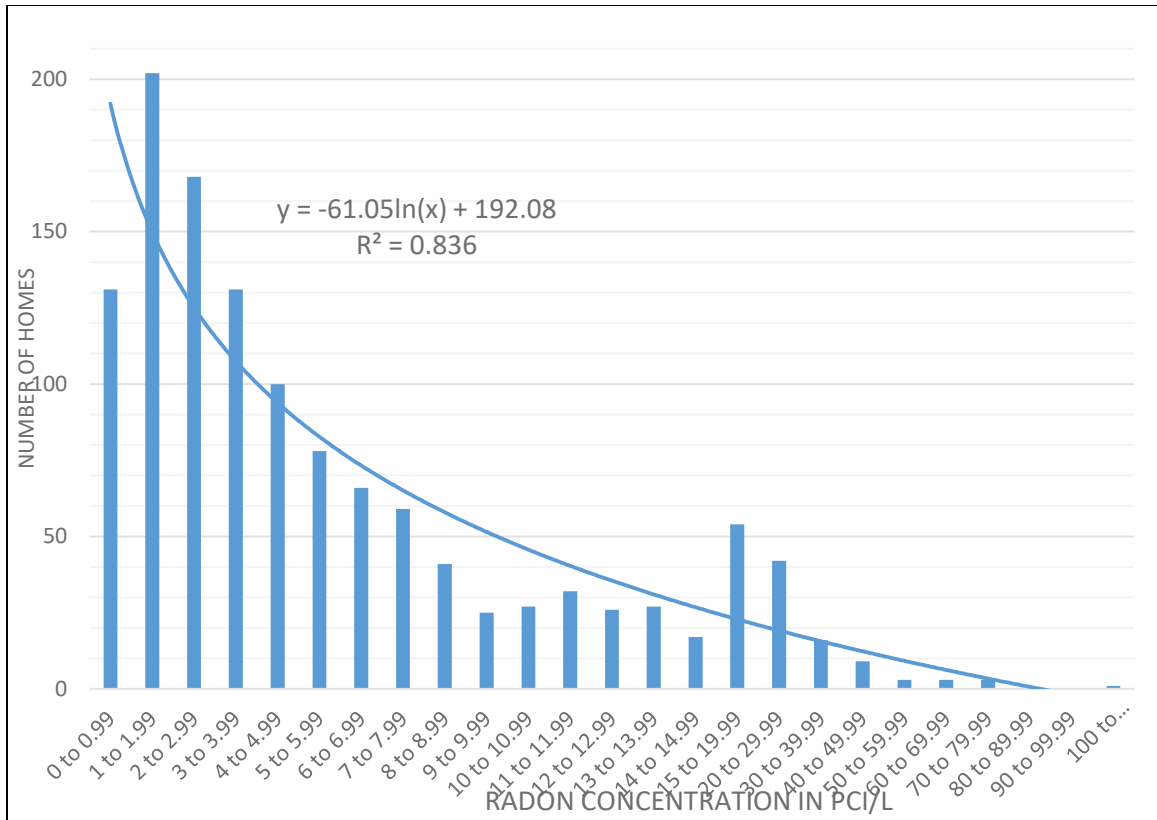


Figure 2.2 Residential Radon Concentration of 1,261 homes built in Amity Township, PA

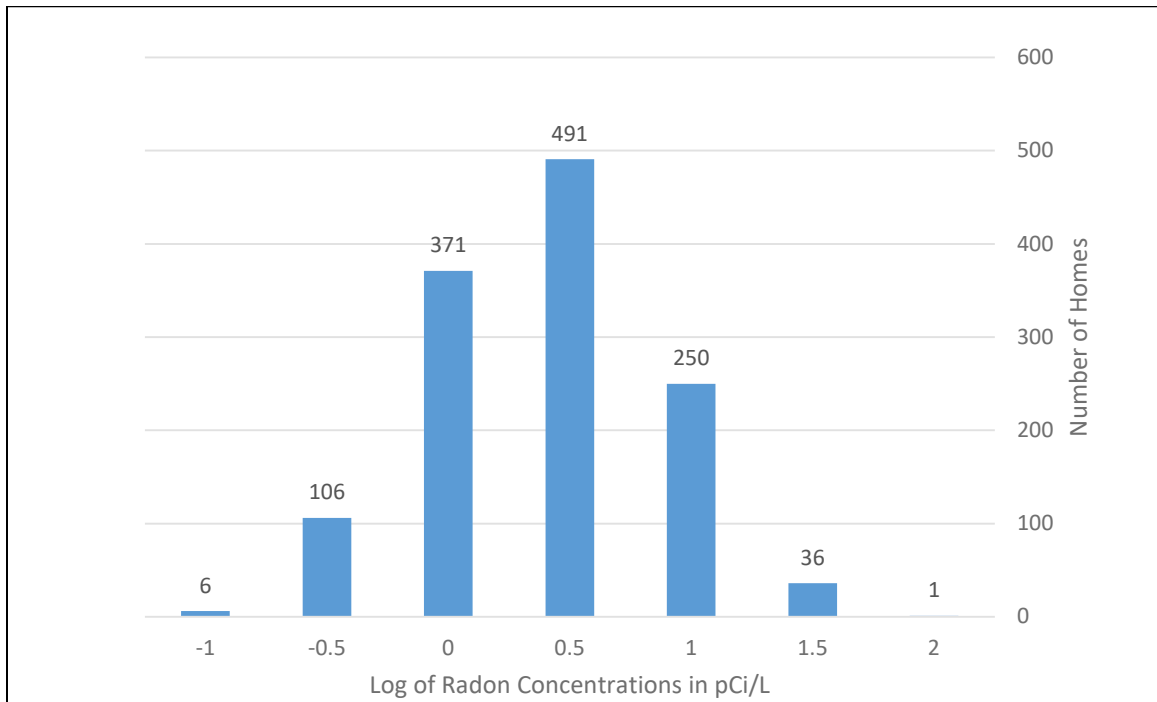


Figure 2.3 Log Transformed Values of the Residential Radon Concentration of 1,261 homes in Amity Township, PA.

Township building permits were obtained using an open records request to determine which homes from the database were built after mandatory RRNC went into effect. The permits mean that these homes were required to have a passive sub-slab depressurization system installed when the homes were built (Loomis, 2014 personal communication ⁵⁸). No testing of the home for radon before or after the passive systems were installed were required, nor were any additional permits needed if the existing system was converted from passive to active. Based on the number of active or certified occupied (CO) issued permits, from 2005 to 2014 there were potentially 347 RRNC built or to be built homes. By utilizing the homes addresses from the permits, 101 (29% of permits) homes out of the 1,261 homes tested for radon in Amity Township were identified as being RRNC (built post 01/01/2005.) The remaining 1,160 homes, in this analysis, will be referred to as non-RRNC (built prior to 2005.) Some of the homes may have been built with radon reduction systems before it was mandatory to do so. In addition, builders obtained the permit before the homes were built, which is why some of the permits were for homes yet to be built in 2014.

Multiple measurements from a single location that were taken on the same day or within 48 hours were averaged together and counted as a single measurement. For non-RRNC, several homes had multiple home measurements at different times, potentially years apart with very different results. While these homes appear to have been remediated, we were unable to verify if that was the case, or how old the home was before it was potentially remediated. Because of this, we used the oldest measurement available per home, since residents would have been exposed to the higher radon levels for an unknown period of time. For the RRNC homes, when there were multiple test

results greater than 48 hours apart with large drops in the residential radon levels, possibly indicating that a fan was installed, thereby converting the system from passive to active, we counted the lowest level. These changes were done soon after the homes were built; as that individuals were unlikely to be exposed to the higher radon levels for very long, if at all. Descriptive statistics were produced using Microsoft Excel such as the geometric mean to characterize radon levels in Amity Township homes.

Results

As expected, initial analysis of non-RRNC and RRNC homes again show a log normal residential radon concentrations distribution due to a tail created by a smaller number of homes having high radon levels, Figures 2.4 and 2.5. This is consistent with other residential radon distributions³⁶. When log transformed, the graphs show a normal distribution. The average arithmetic radon concentration of 1,160 homes built without RRNC or having been remediated is 7.03 pCi/L (260.11 Bq/m³) and the geometric mean is 4.06 pCi/L. Figure 2.4 and Table 2.2 shows that 600 of the 1,160 had radon levels above the national action level of 4.0 pCi/L. The homes built with RRNC had an average arithmetic radon concentration of 5.45 pCi/L (201.65 Bq/m³) and a geometric mean of 2.55 pCi/L. In these homes, only 31 (30.7%) had radon levels above the 4.0 pCi/L action level (Figure 2.5 and Table 2.3.)

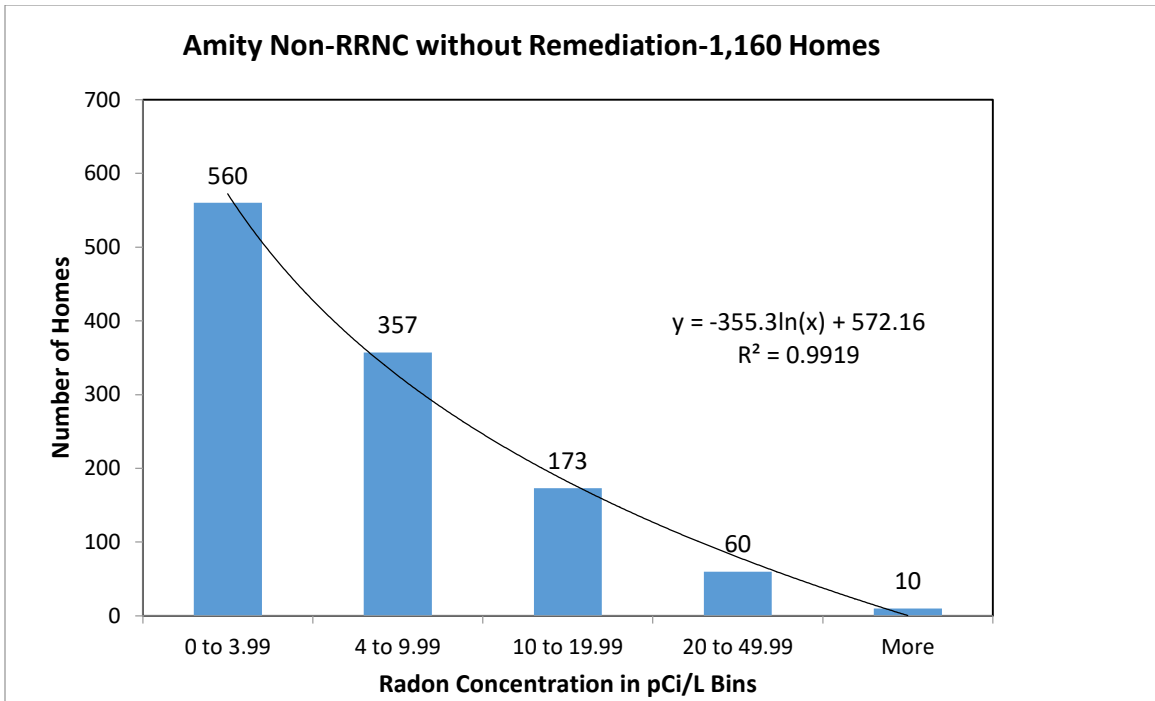


Figure 2.4 Residential Radon Concentration of 1,160 built in Non-RRNC in Amity Township, PA.

Table 2.2 Bin Analysis of the Radon Concentration of the 1,160 Non-RRNC Homes in Amity Township, PA.

Radon Concentration pCi/L	# of Homes	Cumulative %
0 to 3.99	560	48.28%
4 to 9.99	357	79.05%
10 to 19.99	173	93.97%
20 to 49.99	60	99.14%
50 Plus	10	100.00%

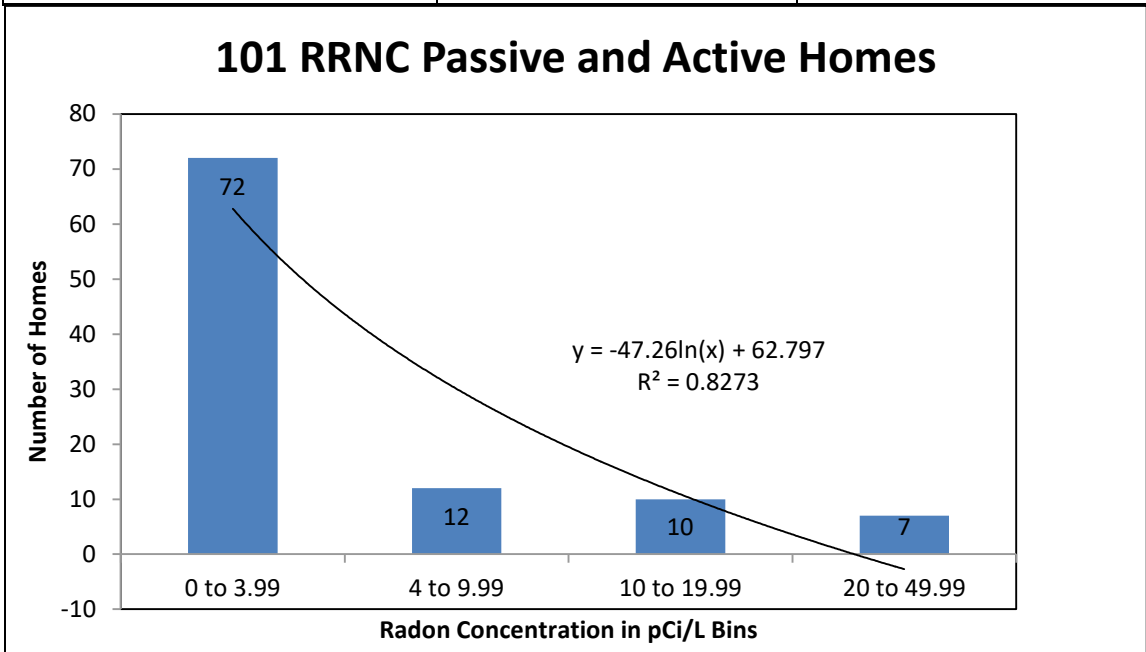


Figure 2.5 Residential Radon Concentration of the 101 homes built RRNC in Amity Township, PA.

Table 2.3 Bin Analysis of the Radon Concentration in the 101 homes in Amity Township, PA.

Radon Concentration pCi/L	# of Homes	Cumulative %
0 to 3.99	72	71.29%
4 to 9.99	12	83.17%
10 to 19.99	10	93.07%
20 to 49.99	7	100.00%
50 plus	0	100.00%

While both the arithmetic and geometric means of the residential radon concentrations were lower in the set of RRNC built homes we studied, statistical analysis was performed to determine if the reduction in radon concentration was statistically significant and not just due to chance. Table 2.4 shows the results of a one-way hypothesis test, that is whether the RRNC homes had statistically significant lower residential radon concentrations. In both sets of data, the distributions around the geometric means (known as variance) were similar so the sample sets are considered homoscedastic. In this analysis, the measure of statistical significance was $\alpha = 0.05$. In the t-Test of the log-transformed data, the p-value of $1.368e-05$ was less than 0.001 which means the results can be considered statistically significant. Because of this equality of variances in the log-transformed samples, we can also conclude ($p < 0.001$) that the reduction in the non-log transformed means of the homes built RRNC versus the non-log transformed homes built without RRNC would also be statistically significant. Additional analysis was performed using the Mann-Whitney test, which confirmed this significance. The Mann-Whitney test analyzed the shift in the medians of the non-transformed data of the RRNC and non-RRNC groups. This table was generated using a statistical program, R version 3.5.0.

Table 2.4 Statistical Analysis of the Log Transformed Residential Radon Concentrations

Comparison of Mean and Median Radon Concentrations in homes built with and without RRNC						
Test Type	Summary Statistics	Non-RRNC Homes (n = 1,160)	RRNC Homes (n = 101)	Test Statistic	Df	p-value
t Test	Mean*	1.402	0.935	T = 4.2099**	1259	<0.001
	SD*	1.062	1.173			
Mann-Whitney Test	Median	4.1	2.2	W = 74388	NA	<0.001

*Statistics reported on log-transformed data

**Test performed on log-transformed data

Conclusion

In Amity Township, PA, for the homes which were built prior to 2005 (non-RRNC), about 5 out of every 10 homes had elevated radon levels. In measurements from the homes built with mandatory RRNC (RRNC), less than 3 out of every 10 homes had elevated levels. This difference represents an almost a 25% reduction in the mean residential radon gas that individuals are exposed to in homes built RRNC versus non-RRNC homes. When using the geometric mean, there is almost a 40% significant reduction in residential radon exposure. Based on my sample data, with 95% confidence, the geometric mean of home of homes built after RRNC was adopted would be between 2.543 and 2.549 pC/Li. The geometric mean of homes built before RRNC was adopted would be between 4.064 and 4.066.

Because the p-value of 1.368e-05 is <0.001, we can conclude that the RRNC has resulted in a statistically significant reduction of exposure to radon in the homes built non-RRNC. Simply put, our analysis shows that the reduction on radon exposure was most likely due to the adoption of RRNC.

Policy Implication:

The results show that 31 of the 101 homes built RRNC with radon measurements appear to have had their systems converted from passive to active soon after the homes were built. This was based on multiple radon concentration tests done at the same

address. The only time Pennsylvania requires radon testing is when a passive system is converted to an active system. The home must be tested for radon concentrations within 30 days starting 24 hours after activation occurs⁵⁷. Based on the results from Amity Township, the passive system installed in the homes reduced the radon to acceptable levels in almost 70% of the RRNC homes. However, it appears that the systems needed to be converted in the remaining homes. The only way to determine if a passive system is sufficient is by post-installation testing. This could be achieved by the use of additional laws such as testing during the sale of a home. At this time, no state requires such testing. The simpler solution would be to adopt a RRNC standard such as RRNC 2.0 which requires post installation pre-occupancy testing.

Chapter 3: Manuscript 2 Reduced risk of lung cancer in Amity Township, PA due to the adoption of a Radon Resistance New Construction (RRNC) building standard.

Abstract: In the previous chapter it was demonstrated that residents of Amity Township, PA living in homes built after adoption of a RRNC standard were exposed to lower residential radon concentrations than Amity Township residents in homes built before the RRNC standard went into effect. In this chapter, we will assess to what extent the reduction of exposure to radon reduces the risk of developing lung cancer using an excess relative risk (ERR) model by Darby, et al. Information about radon exposure will be evaluated along with data regarding smoking status, as demonstrated by this model.

Objective: To investigate the lung cancer risk associated with exposure to residential radon gas for residents in Amity Township, PA and to estimate the reduction of risk for the residents living in homes with reduced radon exposure due to the homes being built with mandatory radon reduction systems.

Methods: The average residential radon concentrations from the data sets representing two sub-sets of Amity Township, PA residential populations (see Chapter 2) will be used, along with the risk of lung cancer based on smoking status, to assess reduced lung cancer risk according to the Darby excess relative risk (ERR) model (Figure 3.1). The two populations are homes built before mandatory RRNC (non-RRNC) and homes built after adoption of RRNC (RRNC.) The Darby ERR model is a peer reviewed lung cancer risk model. The model will be used to determine the relative risk from the residential radon exposure in both populations (RRNC and non-RRNC) and will show that residents in Amity Township in homes built after adoption of a RRNC building standard, due to their reduced residential radon gas exposure will have a statistically significant reduction in their lung cancer risk.

Results: Adoption of a RRNC standard resulted in a 3 to 5% reduction in the relative risk of lung cancer incidence (depending on smoking status). The difference in relative risk due to the radon exposure was greatest in the non-smoking population (5%.) However, current smokers, due to their higher lung cancer baseline risk, living in the non-RRNC homes were at the greatest relative risk for lung cancer compared to never smokers living in the RRNC homes.

Conclusion: Residents of Amity Township, PA living in homes built after RRNC went into effect, regardless of smoking status, have a lower relative risk of lung cancer due to their reduced exposure to radon gas compared to Amity Township residents living in homes built before the RRNC building code was adopted. The relative risk is based only on the residential radon concentrations determined at this point in time. The lower relative risk also means that the probability (chances) of getting cancer will also decrease.

Introduction

Previous publications and chapter 2 have shown that adoption of RRNC is an effective way to reduce residential exposure to radon gas, a known lung carcinogen^{2,3}. But how does this reduced exposure impact lung cancer risk, and how are the public health benefits determined?

Cancer risk models are tools that have been developed to accurately assess the potential to develop cancer from defined exposures or measured characteristics and estimate the cost of cancer burden on the individual and/or the population. These models can be used to determine the probability that individuals or populations exposed to these various risk factors will develop cancer and assist in identifying those at a higher risk for cancer. Certain models can also aide in the evaluation of treatments and interventions.

With a population, such as the residents of Amity Township, the use of a risk model will help to demonstrate the future benefit residents in RRNC homes will gain from the reduced radon exposure.

Several peer reviewed models to evaluate the risk of lung cancer due to exposure to residential radon gas have been developed based on epidemiological studies. The model selected for this analysis is based on the nature of the data about radon, and smoking status that is available for the population of interest. The BEIR VI models were based on pooled analysis of 11 cohort studies of underground miners²⁶, while the Darby (Europe) and Kreski (North America) models were pooled case-control of residential radon exposure and lung cancer^{7,22}. The models all utilized additional risk factors to better quantify the cancer risk from radon exposure such as age, gender, health history and smoking status. While all these risk models can be used to estimate the risk of lung cancer from residential radon exposure, each model is unique and were developed with slightly different assumptions and underlying studies. For instance, the BEIR model was developed based on an all-male population who inhaled the radon gas while working in the physically demanding field of underground mining. Women typically spend more time at home and therefore should have increased exposure to residential radon. Most individuals diagnosed with lung cancer are over the age of seventy⁷¹. All the models considered showed that the risk of lung cancer increases as residential radon concentration increases and all are based on a linear non-threshold dose response (there is no safe level of radon exposure and even small exposures can result in a small increase in the risk of lung cancer). The models also show that the population with the greatest relative risk are current smokers exposed to higher residential radon gas. However, the

greatest proportional increases in relative risk due to the radon exposure among the different smoking categories were seen in the never smoking category. What this meant was that the highest risk of lung cancer due to the radon exposure only was in the never-smokers, although the current smokers had the highest overall (absolute) risk of lung cancer. The models also show a sub-multiplicative effect (greater than additive but less the multiplicative effect) between the two risk factors of radon exposure and smoking when it comes to the risk of lung cancer. This means that the lung cancer excess risk is greater than just that additive effect of the individual risks from each exposure but less than the product of the individual risks. All the models are consistent in showing that the risk of lung cancer increases in a linear fashion as the exposure to residential radon gas increases and that there is no safe exposure level.

How the Darby model handles the smoking status interaction makes it a better fit for analyzing the data utilized in this research. Smoking status can be handled in one of two ways: ever-smoked and never-smoked, or current, former, and never smokers. The Darby model is able to stratify for former and current smokers. Former smokers are at higher risk than never smokers for lung cancer, but their risks compared to current smokers decline the longer they are former smokers. Therefore, being able to differentiate smokers into current and former will give a more accurate estimation of the total excess relative risk of lung cancer due to residential radon exposure.

Methods

Residential radon concentrations from the previous chapter were used as a measurement of radon exposure. From health statistics collected in Pennsylvania, the current, former and never smoking populations of Berks County, PA were used to

represent the smoking populations of Amity Township, PA. (Amity Township is one of the 44 townships located in Berks County, PA.) The radon concentrations and percentages of the populations based on their smoking status were then applied to the Darby ERR models to determine the Amity Township population’s relative risk for lung cancer. According to the Darby model, β is the slope parameter per 100 Bq/m³ of the exposure–response relation based on smoking status (Table 3.1) and X is the mean radon concentration in the homes. Relative risk is determined by adding 1 to the ERR value.

$$\text{ERR} = (\beta)(X)$$

Figure 3.1 Darby ERR Model for Lung Cancer Relative Risk

Table 3.1 Darby β values per smoking status

	Smoking Status		
	Current	Former	Never
β Value	0.07	0.082	0.106

β values per smoking status: The higher value for the never smoker is due to the fact the never smoker has a higher relative risk per unit exposure. Darby et al. 2001.

Table 3.2 Relative Risk of Lung Cancer based on Residential Radon exposure in Amity Township, PA.

RR based on radon only	Smoking Status		
	Current	Former	Never
Non RRNC X=260.11 Bq/m ³ *	1.182	1.213	1.276
RRNC X=201.65 Bq/m ³ *	1.141	1.165	1.214

*Mean Residential Radon Concentrations are from Chapter 2

Table 3.3 Relative Risk of Lung Cancer in Amity Township, PA based on Radon Exposure and Smoking Risk

	Current Smoker RR (95% C.I.)*	Former Smoker RR (95% C.I.)	Never Smoker RR (95% C.I.)
Homes built without RRNC (Pre-2005) Average radon conc 260.11 Bq/m ³	84.519 (68.896, 111.299)	16.379 (13.605, 20.909)	1.276 (1.008, 1.728)
Homes built with RRNC (Post 2005) Average radon conc 201.65 Bq/m ³	81.593 (69.481, 102.354)	15.732 (13.582, 19.244)	1.213 (1.006, 1.565)

*Calculated using the Darby model-a never smoker in a home with zero radon would have a relative risk of 1. *C.I. based on the C.I. of β from table 18 of Darby et al., 2005.

Results

Table 3.2 shows the relative risk of lung cancer based on exposure to residential radon gas without taking the smoking status into consideration. This table shows as residential radon increases, the relative risk from exposure to the radon gas is greater for the never smoker population. When the relative risk from smoking and exposure to residential radon is factored in, current smokers exposed to higher residential radon are at the greatest risk for lung cancer compared to never smokers exposed to lower residential radon (Table 3.3). The probability of getting cancer is highest for current smokers living in homes built without RRNC (higher radon gas exposure.) While the probability of getting cancer is lower for the never smokers, the results also show that never smokers have the greatest proportional increase in relative risk due to radon exposure. This is why residential radon exposure is the leading cause of lung cancer for never smokers. The percent increase in relative risk for those living in homes built non-RRNC compared to those in homes built RRNC was 3.6% (current smokers), 4.1% (former smokers) and 5.2% (never smokers).

Conclusion

Table 3.3 shows that individuals who smoke and are exposed to higher concentrations of residential radon have the highest probability of getting lung cancer. This is mainly due to their higher baseline risk of lung cancer due to their tobacco usage. The risk of lung cancer increased from 3 to 5% depending on the smoking categories with the increase in the residential radon exposure. In the absence of the smoking risk factor, the residential radon exposure becomes the dominant risk factor for lung cancer development. When comparing the relative risk within the individual smoking categories

(to determine the effects on the radon gas alone), the proportional increase in risk for the never smokers was 5.2% higher versus 3.5% for the current smokers when exposed to the higher residential radon gas in the non RRNC homes. This study's results support the results of other studies that without the baseline risk for lung cancer that cigarette smokers have, residential radon gas exposure is the leading risk factor for lung cancer in never smokers.

Chapter 4: Manuscript 3 Cost-effectiveness of adopting a Radon Resistant New Construction (RRNC) building standard as a public health intervention to prevent disease and premature death from lung cancer in Amity Township, PA.

Abstract: The two previous chapters demonstrated that adoption of an RRNC standard by Amity Township, PA was an effective way to reduce residential radon exposure and reduce the lung cancer risk for the residents of Amity Township, PA. In this chapter, a cost benefit analysis (CBA) decision tool will be used to provide additional knowledge on why adoption of the RRNC standard a good public health policy decision would be. For this decision analysis, the CBA tool was used in a systematic way to evaluate potential downstream benefits such as reduced medical costs due to lung cancer prevented against the upfront costs of installing the radon prevention systems in all new homes. Thus, demonstrating that adoption of the RRNC standard is a simple but very effective public health intervention to reduce both the risk of lung cancer and costs from the morbidity and mortality of lung cancer.

Objective: Using a CBA based on a simple decision tree⁷² places monetary values on both the inputs (cost of the radon reduction systems) and outcomes (benefits from prevented medical treatments due to illness prevention.) Using monetary values for both the inputs and outcomes provides insights on whether adoption of a policy provides an overall net gain to society: that is, the benefits from adoption of a policy outweigh the cost of policy adoption. This information will aid but not dictate whether the adoption of radon resistant new construction building standard as an effective public health intervention. The analysis will also determine the potential real world benefits, in addition to demonstrating the potential lives saved. These would be both direct benefits (medical expenses saved because of illness prevention) and indirect benefits (such earning productivity saved due to lack of illness and death from lung cancer.)

Methods: Using a decision tree CBA to do a comparative assessment of all the costs associated with the initial installation of radon resistant features into all new home construction versus homes without radon resistant features (upstream costs) and compare them to the probability and costs of getting lung cancer (including the cost of illness and the cost of death) of the individuals living in the homes with and without radon resistant features. The decision tree will be populated with information from Chapter 3, the relative risk for lung cancer of Amity Township residents living in homes before and after adoption of a RRNC building code standard. The relative risk of lung cancer will be used, with additional data such as incidence and mortality of lung cancer due to smoking, to determine the probability of Amity Township residents getting lung cancer. Both the upstream costs and downstream benefits will be quantitated in monetary units (US dollars (\$)). For the downstream benefits, this will include the medical costs due to treatments for lung cancer and the value of the statistical life (VSL) lost due to lung cancer (value is based on lung cancer due to smoking.) The VSL was used to quantify the benefit of not dying from lung cancer.

Results: The cost benefit analysis shows that there would be a small positive economic benefit due to the adoption of a RRNC building standard, but this is in addition to the future benefit of individuals not getting lung cancer. Based on Amity Township's age adjusted lung cancer incidence rate (Table 1.3), adoption of the RRNC standard is also estimated to prevent 2 to 3 individuals from getting lung cancer. The results appear to also show that some of the homes built RRNC have had their passive systems converted from passive to active. This was based on multiple radon concentration tests done at the same address. The only time Pennsylvania requires radon testing is when a passive

system is converted to an active system. The home must be tested for radon concentrations within 30 days starting 24 hours after activation occurs⁵⁷.

Conclusion: The overall net qualitative benefit due to adoption of a RRNC into Amity Township, PA building codes is estimated to be \$101,246. Overall this is a small cost benefit, but the benefit is statistically significant, and this benefit is based on the prevention of individual getting and dying from lung cancer. This analysis just quantifies the benefit for residents in Amity Township, PA living in homes built RRNC based on their lung cancer risk reduction.

Introduction:

Residential radon exposure is the second leading cause of lung cancer after cigarette smoking. Among the different mortality rates after being diagnosed with cancer, lung cancer has the highest rate of death. Over half of the people diagnosed with lung cancer die within one year of diagnosis and the five-year survival rate for individuals diagnosed with lung cancer is 18%, much lower than for individuals diagnosed with other forms of cancers per the American Cancer Society⁷¹. Because of its severity, prevention of lung cancer such as by reducing exposure to environmental risk factors like residential radon is an important public health prerogative⁷⁰.

Multiple studies on residential radon have shown that individuals exposed to elevated residential radon levels are at increased risk for lung cancer³². Radon is the primary cause of lung cancer in non-smokers. As previously discussed, case control analysis carried out in both Europe and North American found that relative risk of lung cancer increased about 8 percent when residential radon exposure increased by 100 Bq/m³ (about 2.7 pCi/L/m³.) Chapter 2 and other publications have shown that adoption

of a RRNC standard is an effective method to reduce residential radon exposure.

Reduction of radon exposure reduces population lung cancer risk⁷³. The results of this decision tree cost benefit analysis clarify the potential benefits from RRNC's lung cancer risk reduction. This information will provide additional support on why adoption of a RRNC standard would be a desirable public health intervention.

Methods:

Economic evaluation to compare the costs and impacts of adopting RRNC was carried out by decision tree cost-benefit analysis. The analysis will be based on homes built with and without RRNC in Amity Township, PA and their respective relative risks for lung cancer. The relative risk will be used in conjunction with additional data, such as the population's smoking status, to determine the resident's probability of getting lung cancer. The probabilities will then be used to calculate the downstream costs.

Cost Benefit Analysis:

In this type of economic evaluation, both the economic costs implementing RRNC and potential health benefits (from the reduction in costs due to lung cancer prevented) are expressed in US dollars. We compared these to the costs in homes built non RRNC. The cost benefit analysis utilized a decision tree. The decision tree⁷⁴ is a structured way to estimate the risk and rewards with and without adopting RRNC in Amity Township, PA by quantifying an outcome of disease or no disease (lung cancer). In this situation, the outcome or the probability of getting cancer is quantified in the cost of getting lung cancer (including treatments and mortality). The decision tree will show that applying and paying upfront for the radon prevention measure when the home is built (RRNC) is more cost effective than paying for the higher costs of illness and death from

lung cancer that will be prevented (preventable total cancer costs)⁷². A simple decision tree is shown in Figure 4.1. The probability of getting lung cancer for individuals living in homes with and without RRNC was determined by utilizing the Darby model and Amity Township residential radon concentrations. The actual decision tree will also be expanded to consider not just living in a home with and without RRNC, but also smoking status.

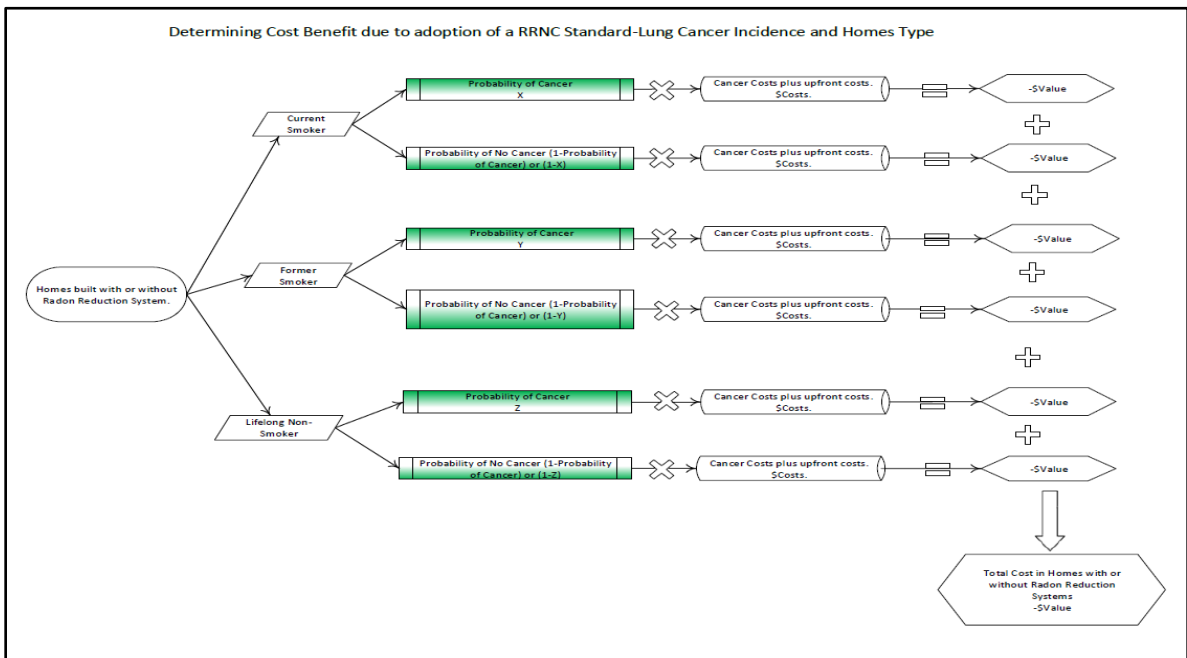


Figure 4.1 Simple RRNC-Cancer Decision Tree

Specific information was needed to model the potential benefits of having RRNC. These included the additional cost of installing the RRNC system when building a new home and the total cost of getting sick from, and then dying of, cancer. The probability of Amity Township residents getting cancer and then dying from cancer had to be determined based on smoking status (current, former and never) and residential radon exposure (RRNC and Non-RRNC.) The Darby relative risk of lung cancer from residential radon exposure was used to determine the probability.

According to the National Radon Program Services (a cooperative program run by Kansas State University and the US EPA) building radon resistant features into a new construction ranges from \$250 to \$700⁷⁵. For our analysis we used the value in the middle of the estimated range, \$500. The cost to build a home with a passive radon resistant system is much cheaper than installing a system after the home is built (known as remediation). In Pennsylvania, the cost to remediate a home can run upwards to \$2,000⁷⁶.

The estimated cost of lung cancer was based on the cost of treating a person from diagnosis and the cost of mortality (individuals diagnosed with lung cancer are usually found to be stage 3). Stage 3 diagnosis means that the cancer cells which were initially found in the lungs are now found in both the lungs and the lymph nodes surrounding the lungs. The stage 3 diagnosis contributes to the low 5-year survival rate of about 18%. The cost of cancer used in this analysis was calculated for five years of treatments. According to Mariotto et al., 2011 the initial cost of treatment for the first-year post diagnosis (combined for both male and female) would be \$72,851, continuing cost per year for treatments would be \$7,861 for years two through year four post diagnosis, and the final year of treatment would be \$140,881 based on annualized mean net costs of care in 2010 US dollars⁷⁷. The total cost for 5 years of treatment would be approximately \$237,315 in 2010 US dollars.

To quantify the benefit of avoiding lung cancer fatality, the value of life was calculated based on the average Value of Statistical Life (VSL) from Viscusi and Hersch, 2007⁷⁸. They determined that the VSL for smokers was \$7.32 million and \$7.39 million for non- smokers. Being a smoker reduced the value of a person's life (and increased the

person’s chances of dying from lung cancer). Please note this is combined for both males and females. Men have a higher VSL than women (this is based on the fact that woman earn about 40% less for every dollar a man earns.) However, for the purposes of this research, populations were not divided by gender. Based on the data described, the total cost of being diagnosed and then dying from lung cancer would be \$7.61 million for non-smokers \$7.53 million.

Results:

The probability for individuals in Amity Township to get cancer was based on the probability of getting cancer based on smoking status multiplied by the relative risk in each category per radon exposure (in homes built with and without RRNC). Table 4.1 contains the smoking percentages of the population of Berks County. Figure 4.2 shows probability of getting lung cancer in Amity Township based on the relative risk for individuals to get lung cancer based on their radon exposure and smoking status multiplied by their probability of getting cancer based on their smoking status. The process is the same for determining the probability of dying from lung cancer in Amity Township based on radon exposure and smoking status. The probability of getting cancer based on Amity Township is shown in Table 4.2 and the probability of dying from lung cancer in Amity Township is shown in Table 4.3.

Table 4.1 Berks County, PA Smoking Population Percentages

	Percentage of Current Smoking Population		
Berks County, PA 2015	23%	26%	51%

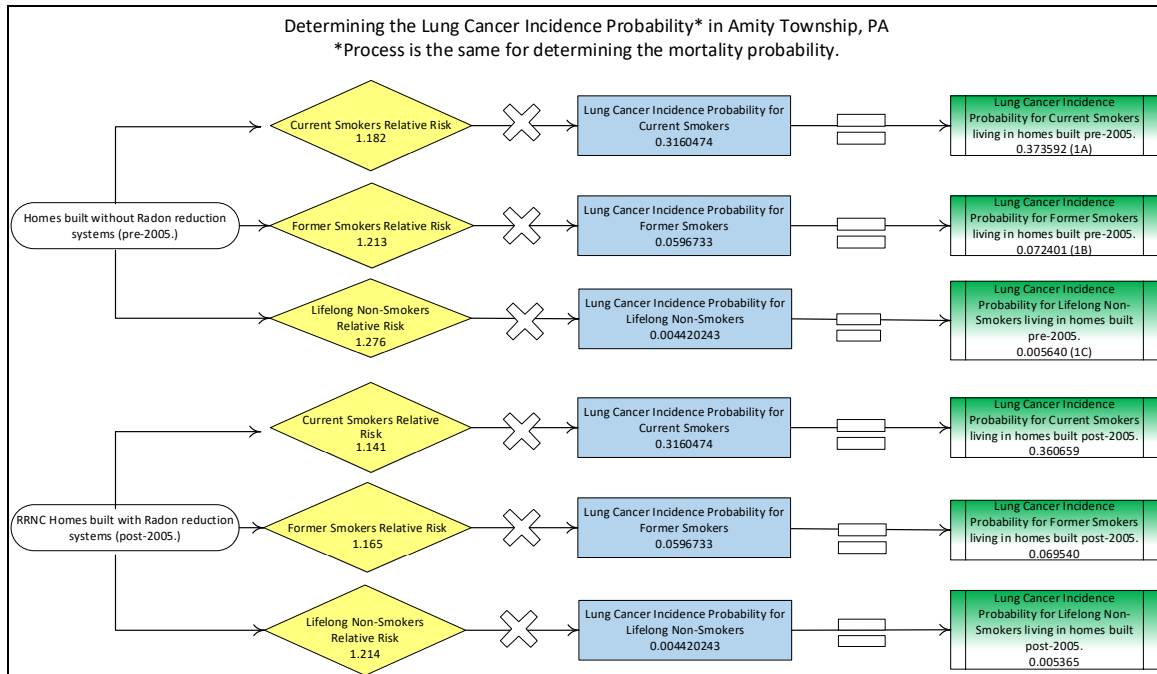


Figure 4.2 Lung Cancer Incidence Cost Benefit Analysis of homes built Non-RRNC (Pre-2005)

Table 4.2 Amity Township Lung Cancer Incidence Probability

	Current Smoker	Former Smoker	Lifelong Non-Smoker
Non-RRNC (Pre-2005 Homes)	0.373592	0.072401	0.005640
RRNC (Post-2005 Homes)	0.360659	0.069540	0.005365

Table 4.3 Amity Township Lung Cancer Mortality Probability

	Current Smoker	Former Smoker	Lifelong Non-Smoker
Non-RRNC (Pre-2005 Homes)	0.309161	0.059914	0.004666
RRNC (Post-2005 Homes)	0.298458	0.057547	0.004440

The probability of getting, and possibly dying from, lung cancer in Amity Township is reduced for the individuals regardless of smoking category, living in homes built RRNC, due to the reduced residential radon exposure.

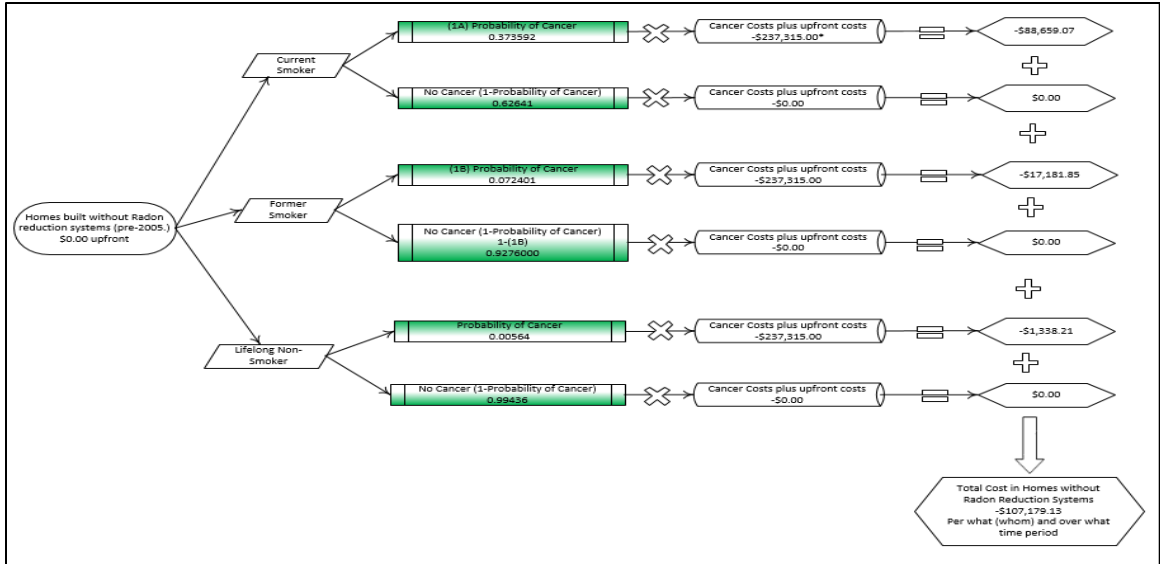


Figure 4.3 Lung Cancer Incidence Cost Benefit Analysis of homes built RRNC (Post-2005).

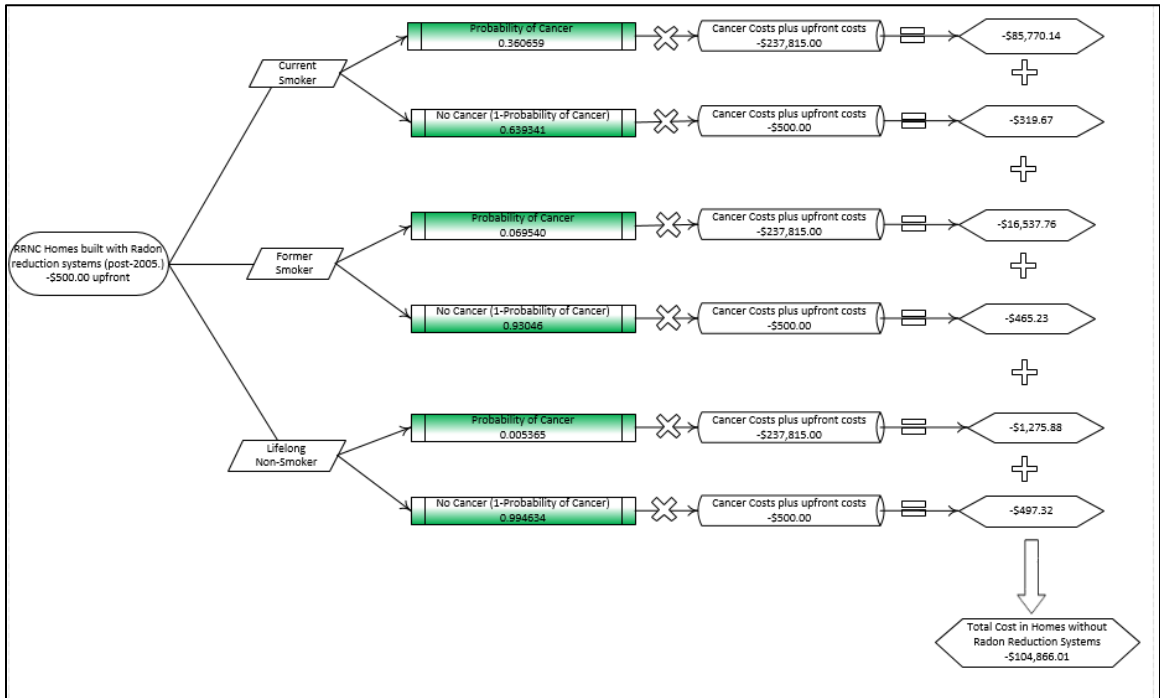


Figure 4.4 Lung Cancer Mortality Cost Benefit Analysis of homes built Non-RRNC (Pre-2005).

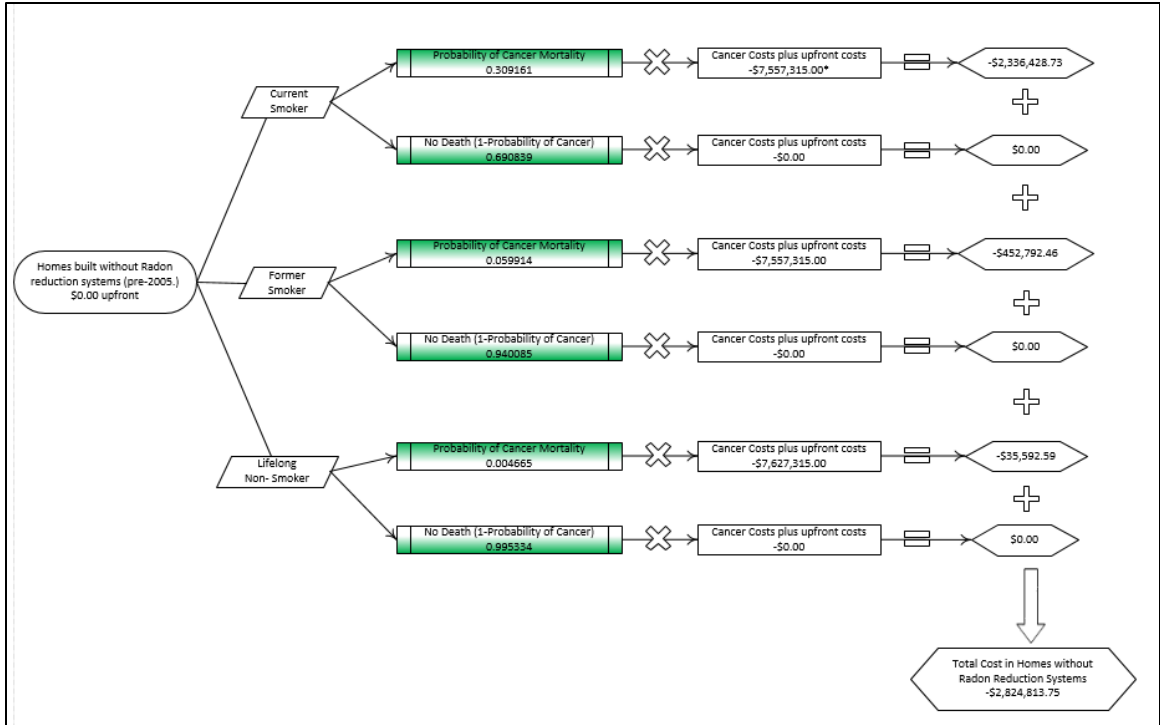


Figure 4.5 Lung Cancer Mortality Cost Benefit Analysis of homes built RRNC (Post-2005).

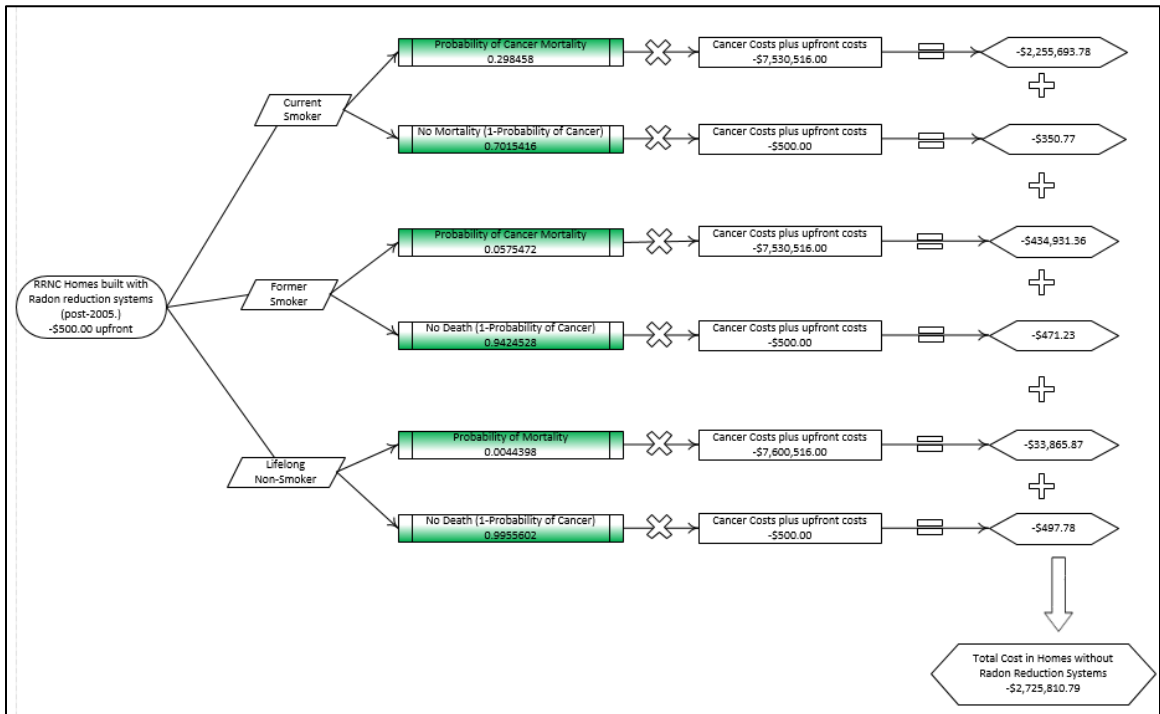


Figure 4.6 Lung Cancer Incidence Cost Benefit Analysis of homes built Remediated Non-RRNC (Pre-2005).

The cost benefit analysis indicates that the benefit based on the reduced probability of not getting or dying from lung cancer will eventually provide a benefit

(savings) that will outweigh the initial cost of installing RRNC in the homes of everyone, including the large number of people who will not get lung cancer.

After the initial cost benefit analysis was complete, an additional scenario was considered. In the second scenario, the risk and cost of having the non-RRNC remediated (having a radon reduction system installed after the home was built) was factored in. We determined the probability and cost of remediation based on the data from the non RRNC homes in Amity Township, PA. From these homes, 41% of the radon measurements are in the range for which the EPA would recommend remediation. Of those homes, based on multiple radon concentration tests, 28% appear to be remediated. Based on these numbers, when a non-RRNC home is sold, it was calculated that there is an 11.5% chance (probability) that the home would be remediated. The cost for remediation, determined using a decision tree (Table 4.4) is \$2500. The results were similar to the first tree, however in this analysis the cost benefit analysis increases slightly for adoption of RRNC. Full Decision trees, analysis and other information can be found in Appendix C.

Table 4.4 Decision Tree to Determine the Upstream Cost for Home Remediation

	Probability	Cost	Output
No Remediation	0.885	\$0.00	-\$287.00
Remediation	0.115	\$2,500	

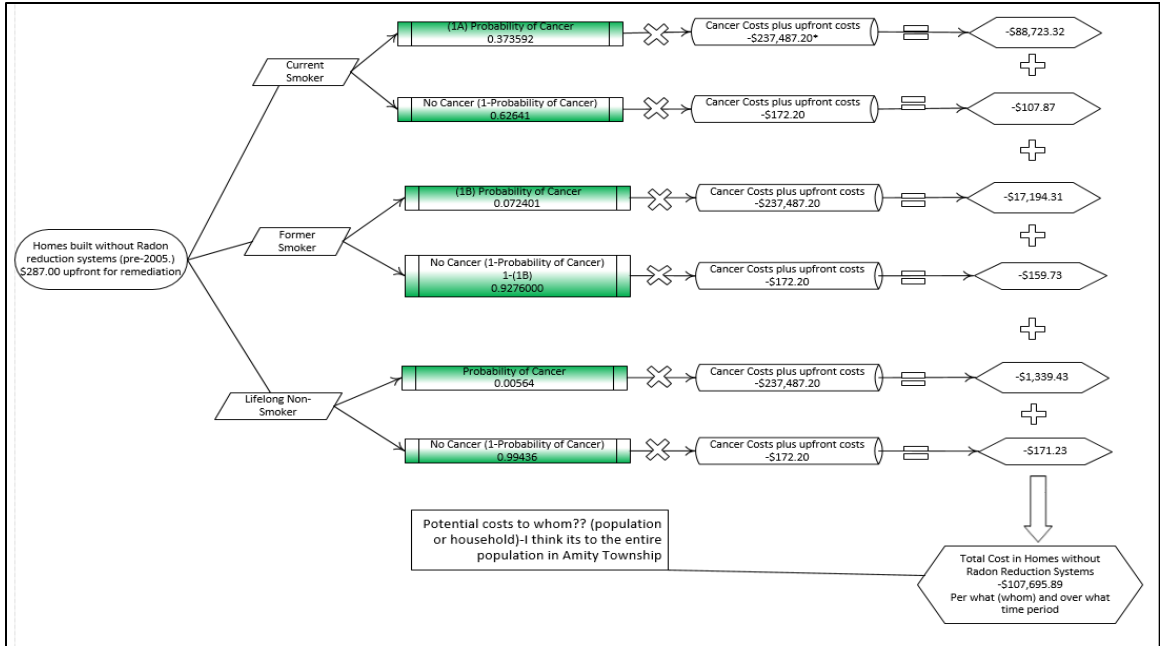


Figure 4.7 Lung Cancer Mortality Cost Benefit Analysis of homes built Remediated Non-RRNC (Pre-2005).

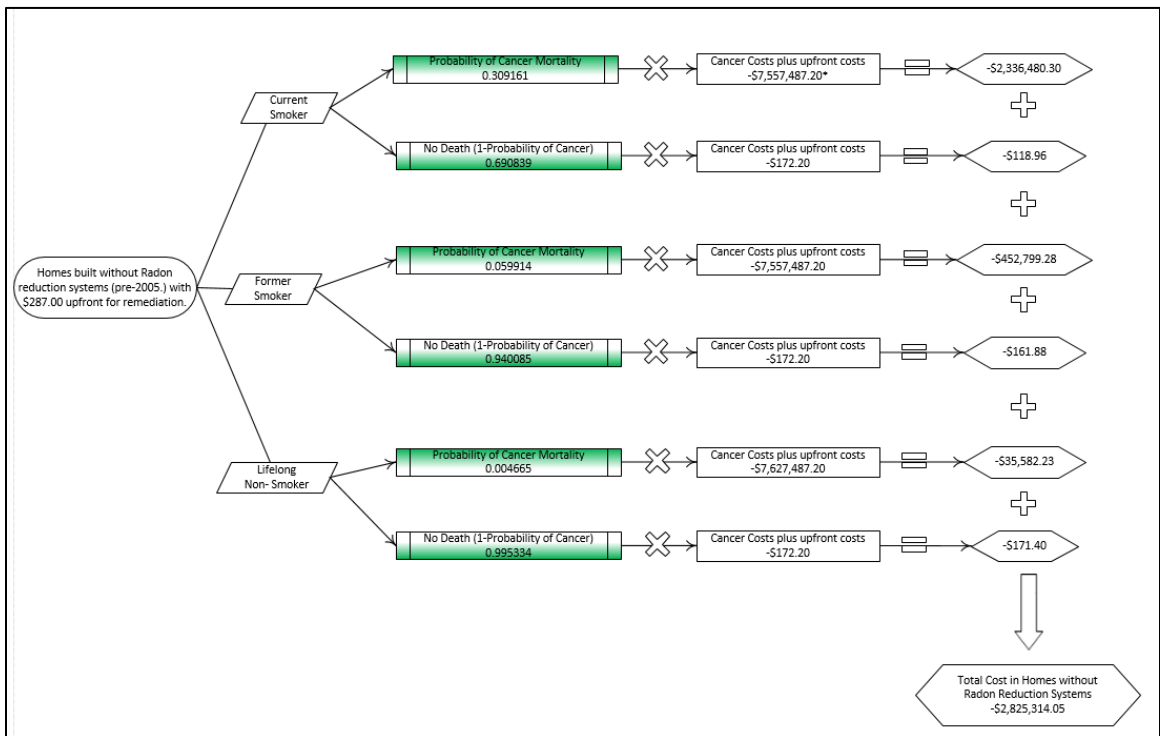


Figure 4.8 Lung Cancer Mortality Cost Benefit Analysis of homes built Remediated Non-RRNC (Pre-2005).

Conclusion

Adoption of a RRNC provides a small cost benefit in addition to the health benefit of reducing the risk of lung cancer. The potential estimated savings due to the adoption of RRNC by Amity Township, PA as a whole was \$101,246.08. The savings increase slightly to \$102,333.14, when factoring in the estimated cost to remediate homes built without RRNC (based upon the estimated number of homes that appear to be remediated from the Pennsylvania database of radon measurements.) These cost savings belie the fact that Amity Township, PA residents living in homes built prior to 2005 (built without radon reduction systems) are at a 3.8% increased risk for developing lung cancer compared to residents living in newly constructed homes built with radon reduction systems.

Chapter 5: Policy Considerations and Discussion Overview

Lung cancer is one of the most aggressive cancers. The most current data from the American Cancer Society shows that the 5-year survival rate after lung cancer diagnosis is only 18%. As previously discussed, exposure to residential radon gas and its decay products are estimated to cause between 10% and 15% of lung cancer incidence. It is the second leading cause of lung cancer after cigarette smoking and is the leading cause of lung cancer in non-smokers. To reduce the risk of lung cancer from residential radon gas, one must reduce exposure to the radon gas.

In Chapter 2, it was demonstrated that adoption of the radon resistant building standard Appendix F was an effective method to reduce residential radon exposure in Amity Township, PA. Chapter 3 evaluated the reduction in the lung cancer risk due to the reduced radon exposure after adoption of Appendix F. In addition to the health benefit from adopting Appendix F, Chapter 4 demonstrated the cost benefit that Amity Township, PA and its residents will gain due to adopting Appendix F. Chapter 4 also demonstrated that the benefits of avoiding the future economic burden of lung cancer morbidity and mortality costs by building a home RRNC would be greater than the initial costs of building the homes RRNC in Amity Township, PA. Therefore, adoption of Appendix F by Amity Township, PA was a cost-effective method to reduce residential radon exposure and reduce the township's risk of lung cancer.

Policy Options:

There are several different options for effectively reducing residential radon exposure during new home construction.

- Option 1: “Building radon out passively” by requiring newly constructed homes to have passive features or systems that reduce and/or remove radon gas from the home;
- Option 2: Radon disclosure during real estate transactions, specifically radon awareness disclosure which can apply to both existing and new home stock (such as in Minnesota);
- Option 3: “Building radon out actively” by requiring newly constructed homes to have active features or systems that reduce and/or remove radon gas from the home;
- Option 4: Requiring a standard with post-installation testing for passive radon systems, with remediation to active systems when appropriate.

Option 1: Building radon out with passive systems. The basic components of a passive sub-slab or sub-membrane depressurization system such as the International Residential Code (IRC) Appendix F that applies to one- and two-family dwellings of three stories or less located in EPA identified Zone 1 areas. The basic radon reduction system consists of:

1. A layer of gas-permeable material such as gravel covered by plastic sheeting/gas retarder layer which goes below the house’s foundation.
2. A perforated pipe (which is placed within the gravel) attached to a PVC pipe that traverses through the foundation and travels throughout the house to twelve inches above the roof.

3. A junction box placed under the roof within 6 feet of the vent pipe, to power a radon exhaust fan (if needed later).

Results from Amity Township, PA show that adoption of Appendix F RRNC standards into their building codes is a simple but effective public health policy to protect people from residential radon exposure and reduce the risk of lung cancer. The risk of getting lung cancer due radon exposure is 1.036, 1.04 and 1.051 times higher for individuals living in homes without RRNC based on smoking status respectively (current, former to never smoker) in Amity Township, PA. While the reduction in risk is small, due to the heavy burden of illness and high mortality rate associated with lung cancer, the future savings due to the reduction in lung cancer costs is higher than the initial cost of building all new homes with a radon reduction system. The cost of getting cancer combines the medical costs of treatment, the costs of lost wages due to illness (current earnings) and death (future earnings) or life years lost. The cost benefit analysis of the current research data demonstrates a small but positive overall net benefit of about \$76,000 to the residential population as a whole in Amity Township, PA due to the reduced lung cancer risk. For every 1,000 individuals living in homes built RRNC in Amity Township, PA compared to those living in non-RRNC, the reduction in radon exposure translates to an estimated 2.9 (0.3 %) people who will not get lung cancer over their lifetimes.

Nevertheless, installation of a passive RRNC system does not reduce radon levels to below 4.0 pCi/L in all cases. Passive systems have been shown to reduce residential radon levels by about 50%, which gets most homes below the national action level. Appendix F does not require installation of a fan or pre-occupancy testing to determine if

the fan is needed. The state of Minnesota adopted Appendix F, which went into effect in 2009 (MN Statute 326B.106 subd 6). In 2014, testing of new homes built after 2009 found that 1 out of 5 homes had levels above 4.0 pCi/L, compared to 2 out of 5 homes with levels above 4.0 pCi/L in the overall building stock (MDH 2014.) This shows that adoption of a RRNC standard does reduce residential radon exposure and reduces the lung cancer risk. However, based on the state's own data, this still leaves about 20% of Minnesota residents buying new homes unknowingly at risk for exposure to elevated radon levels. While the overall residential radon concentration concentrations were lower, 30% of the homes in Amity Township built with the passive radon reduction system would require the additional radon reduction capabilities from converting the passive system to an active one to get the homes radon concentrations below the national action level.

Option 2: Radon disclosure that informs potential buyers if a home was tested and the results of the test for radon during real estate transactions. States may have residential radon disclosure laws that require disclosure of known radon levels, but do not require testing. Some state laws also require notification to the buyer of the risk of residential radon exposure and the benefits of getting a home tested. The state law determines whether these disclosure laws apply to existing homes only, or to existing and newly-constructed homes (never occupied). As of 2012, more than half of the states with radon disclosure laws have exempted new construction ¹⁹. Minnesota is an example of a state whose law applies to existing homes and new construction, requires mandatory disclosure of detailed radon information, and a specific radon warning statement that recommends all homebuyers conduct a radon test. There was an increase in the testing of

residential radon levels after awareness disclosure laws were passed in Minnesota. A similar law was enacted in Illinois. Nevertheless, while radon notification laws can be effective in increasing testing rates, there will still be many home purchasers who do not test.

Notification disclosure could apply to newly constructed home stock and could require any information about radon systems that have been installed and/or any radon testing/results performed on the property. This may increase testing of new homes. However, if a home purchaser is informed that the home has a passive RRNC system, the purchase may believe that no further testing is needed. Unless testing is required, many individuals in newly built homes will not find out that they need to convert their system from passive to active. At this time, no states have adopted mandatory testing during the real estate transaction, though at least one local jurisdiction (Montgomery County, Maryland) has done so ⁷⁹.

Option 3: Building radon out with active systems. A policy requiring active RRNC for all newly built homes would save lives by bringing about greater reductions in residential radon gas compared to passive RRNC systems. Active systems have been shown to reduce residential radon levels by 80 to 90%, compared to 50% for passive systems ⁷⁰. However, such a policy would have a negative benefit-cost ratio, higher cost for very little additional health benefit. While there is no safe level of radon, for most homes the passive systems would be sufficient to reduce residential radon concentration to below the current radon action level. In the case of RRNC homes in Minnesota, 80% of the homes would not need an active system (to reduce radon levels below 4.0 pCi/L). For this reason, it may not be a realistic policy option for many jurisdictions. Based on

the data from homes built RRNC in Amity Township, PA, 70% of the homes would not need the active system in order to achieve the action level of 4.0 pCi/L.

Option 4: Adding mandatory post-installation testing of passive systems, with remediation to active systems when testing demonstrates levels above 4.0 pCi/L, to a “building radon out passively” requirement for newly constructed homes. Post-installation testing prior to home occupancy would increase potential future health benefits for localities that adopt a RRNC standard. The benefit of post-installation testing is to determine whether the system is working properly and is adequate for reducing the residential radon present in the house to below the action level or should be converted from a passive system to an active system by installing a fan. In the RRNC homes in Amity Township, 30% of the homes built with passive radon reduction systems had residential radon levels above the current action level of 4 pCi/L.

ANSI RRNC 2.0, like IRC Appendix F, requires a passive soil depressurization system for newly constructed homes. Unlike Appendix F, this standard also requires post installation pre-occupancy testing of residential radon levels for certification. If the levels are higher than the national action level, currently 4.0 pCi/L, the reduction system must be converted from passive to active to receive certification.

Adoption of a standard such as ANSI RRNC 2.0 would provide a greater health benefit over another standard that requires construction of the passive system alone, with minimal additional cost. Most homes would pass the pre-occupancy testing without having to convert the passive to an active system to reduce radon exposure, and their additional cost would be that of the testing. In Minnesota, this would be the case for 80% of all new construction. Based on the analysis of the Amity Township data, the passive

systems would be sufficient for 70% of all the newly constructed homes. Thus, requiring testing following installation of a passive system, along with activation of the system where necessary, would better protect public health and would be a more cost-effective intervention to reduce the risk of lung cancer from residential radon exposure than adoption of IRC Appendix F or other standard requiring only the installation of a passive radon system. This policy approach could be carried out through adoption of the ANSI RRNC 2.0 standard, by adopting a modified Appendix F, or through other similar regulatory provisions, at the state or local level.

Policy Discussion on Radon Laws (other than RRNC)

This study demonstrated that adoption of a RRNC building code would be an effective public health intervention to reduce the lung cancer risk from residential radon exposure. The key to this analysis was the availability of data: in this case, results of residential radon testing. Pennsylvania is one of several states that require reporting of radon testing. Analysis of the database now shows why adoption of an RRNC standard would be a good decision by other localities for their new construction. In addition, the locality should also adopt a law for collecting the residential radon measurements as a way to test the effectiveness of the RRNC building code. At this time, the other states that require reporting of radon test results include Florida, Illinois, Iowa, Kansas, Maine, New Jersey, and New York.

Another observation based on the analysis of radon measurements for the homes in Amity Township, was the results of multiple test results from a home. The multiple results varied from being submitted on the same date, several days apart, to tests submitted years apart. The tests result either showed consistent results or decreasing

radon concentration levels. The consistent test results are most likely due to testing following the EPA recommendation of 2 short term tests, with the second test starting immediately after finishing the first test. The homes with decreasing radon concentration levels appear to indicate that the homes not built RRNC have been remediated. In remediation, the radon reduction system is added to the home after it is built. A home that is remediated has a depressurization system, usually active, installed into the home. The final possibility is that a home built RRNC has been converted from a passive system to an active system by installing a radon fan. Knowing how many homes have been mitigated or converted from passive to an active system would be useful in demonstrating the need for building a home with a radon reduction system. Additionally, the knowledge would show why testing after a system is installed is important - to identify the homes in which a passive system is not enough to reduce the home residential radon concentration to below the action level.

Adoption of RRNC building code standard is an effective intervention to reduce the risk of lung cancer from residential radon exposure. Coupled with requiring collection of radon test results, the adoption would provide a way to show the benefit of the RRNC building standard by observing the reduction in radon concentration.

Appendices

Appendix A: Measurements of Risk

Absolute Risk

The absolute risk is the actual risk of developing a disease, lung cancer, over a lifetime. Smokers have a higher absolute risk of developing lung cancer than non-smokers due to sub-multiplicative interaction between radon exposure and smoking, the absolute risk for a smoker exposed to radon is greater than just adding the individual's risks from either smoking or exposure to radon together.

Relative Risk

The relative risk is the chance of disease happening when two risks are compared, but this doesn't demonstrate the actual risk of developing disease. When comparing non-smokers to smokers in the relative risk of exposure to different residential radon concentrations, relative risk increases with increasing radon concentration. Due to lower baseline lung cancer risk, the relative risk due to increasing residential radon is higher in non-smokers versus smokers. But the absolute risk will still be higher in smokers because the risk of lung cancer is much higher to versus non-smokers.

Appendix B: Risk Based Decision Planning Template

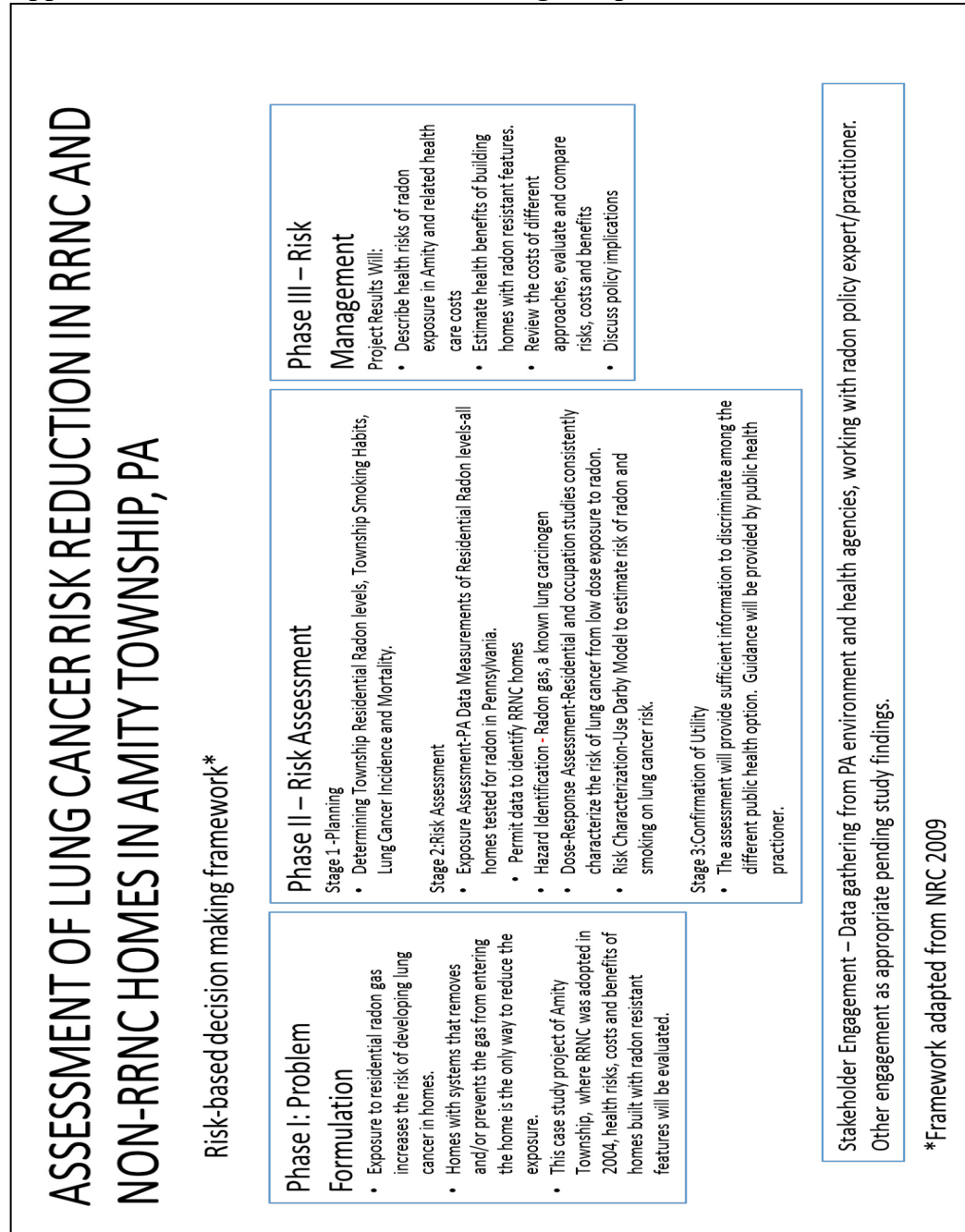


Figure Appendix 1.1 Risk-Based Decision Framework

Appendix C: Cost Benefit Analysis

Cost Benefit Analysis

Data Analysis Inputs

The cost of adding radon resistant features to new home construction (RRNC) ranges from \$350 to \$500 according to National Radon Program Services, a cooperative program of Kansas State University and the EPA.⁸⁰ In Pennsylvania, the cost to add a simple system to an already built home starts around \$800 but can also cost \$2500⁸¹.

The relative risk (RR) of getting lung cancer in Amity Township, PA was determined using the Darby Model. In this model, the relative risk was based on residential radon concentrations and current smoking status. We were then able to determine the relative risk status based on smoking status (current, former and never smoker) and residential radon (RRNC and non-RRNC.) Former smokers risk for developing lung cancer are lower than current smokers but higher than never smokers. The RR ranged from 1.21 for a non-smoker in a home built with a RRNC system to 84.52 relative risk for a current smoker in a non-RRNC home. Input data utilized the average residential radon levels from homes in Amity Township, PA using radon measurements from PADEP. The homes were divided into non-RRNC (homes built before 2005) and RRNC (built after 2005) based on permit data. Currently, smoking status can only be determined at the county (Berks) level from the Behavioral Health Risks of Pennsylvanian Adults study (BHRPA.) In 2015, 23% of the adult populations of Berks County were identified as current smokers. The lung cancer incidence and mortality rates were calculated for Amity Township using estimated age group (based in 2010 census) from FactFinder from the US Census and actual counts of lung cancer incidence and mortality from Pennsylvania Department of Health, Bureau of Health Statistics and

Research. The 2015 probability of cancer incidence (0.0690) and mortality (0.0571) values were from the American Cancer Society⁸².

The cost of getting cancer combines the medical costs of treatment and the costs of lost wages due to illness (current earnings) and death (future earnings.) The five-year survival for the more common non-small cell lung cancer depends on stage diagnosis. Survival, based on all stages combined, according to the most current SEER Cancer Statistics Review is 17.7% for all gender and races combined. Individuals diagnosed at stage 1 have a survival rate at about 55.2 % while diagnosis at stage 4 (metastatic) is only 1% according to the American Cancer Society. Lung cancer is usually diagnosed or found when the cancer is at stage 3, when the cancer has spread from the lungs to lymph nodes both closest to the lungs (3A) and those further away (3B). At this stage, the five-year survival rate is 4.3% for stage 3B up to 14% for stage 3A.

According to the Mariotto et al., 2011, the annual costs in US dollars for cancer treatment for lung cancer in 2010 US dollars was estimated to be NIH, the initial cost of treatment for the first-year post diagnosis in (combined for both male and female) would be \$72,851, continuing cost per year for treatments would be \$7,861, and the final year of treatment is \$140,881. Because of the low five-year survival rate, the medical costs were determined for getting lung cancer to be \$237,315.00 for five years from initial diagnosis to death, the first and last year of treatment, plus three years of continuing treatment. SEER Cancer statistical review found the average years life lost (AYLL) for all races and gender combined was 15.2, which was about the middle of the grouping. However, for person years life lost, \$2,372.2 (for all ages and genders) were the highest. The second-place cancer, colon & rectum, value was \$799.7. The cost of death will be based on the

average Value of Statistical Life (VSL) from Viscusi and Hersch, 2007⁷⁸. They determined that the VSL for smokers was \$7.32 million and \$7.39 million for non-smokers. Please note this is combined for both males and females. Men have a higher VSL than women (due to mainly to the fact that for every dollar a man earns, a woman earns less.) However, for the needs of this research, populations were not divided up by gender. For non-smokers, the total cost of getting lung cancer would be \$7.61 million and for smokers \$7.53 million.

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EMPLOYMENT HISTORY:

Supervisory Consumer Safety Officer (O-6 Billet) Temporary 123 Day Detail

07/2018 – 11/2018

5001 Campus Drive, College Park, MD 20740 United States

The Product Evaluation and Labeling Team (PELT) is responsible for developing regulations, policy, and guidance for the labeling of conventional foods, managing temporary marketing permits, menu labeling, gluten-free and allergen labeling, and ingredient naming. During the detail I supervised six technical staff members. In my time as the supervisor I reviewed and/or provided edits and input to over sixty different documents related to the work done by the PELT team members.

Quality Assurance Specialist (O-5 Billet) Temporary 120 Day Detail

12/2017 -04/2018

5001 Campus Drive, College Park, MD 20740 United States

The Quality Management Team (QMT) in the Office of the Center Director QMT administers or advises on work concerned with assuring the quality of laboratory and business processes and delivery of services needed to carry out the Center for Food Safety and Applied Nutrition (CFSAN) programs and functions. QMT implements programs, plans and conducts audits for quality assurance throughout the Center to fulfill the Center and FDA's mission and regulatory requirements. During the detail, I researched and authored a Standard Operating Procedures (SOP) for submitting all the Center's Bioresearch Monitoring (BIMO) Assignments.

Analyst-Expert Consumer Safety Officer (O-5 Billet)

06/2011 - Present

5001 Campus Drive, College Park, MD 20740 United States

OFS-CAEMS reviewer: monitors, reviews, and investigates reports of all FDA regulated food products submissions to CFSAN's Adverse Events Management System (CAEMS). CAEMS is a monitoring tool to identify potential public health issues relating to FDA regulated products. Provides analyses of data from the CAEMS database to help support regulatory actions. High priority events are typically reviewed within two days of notification. Serves as the division liaison for the reportable food registry/risk control review weekly meetings. Furnishes in-depth technical information to upper level management that supports enforcement or regulatory actions and provides recommendation when it comes to pathogen survival in foods. Assumed responsibilities for reviewing certificates of free sale (COF), in addition to my own job duties, for several months. During this time, drafted a procedures document to assist with training staff on

handling COFs, and to provide consistency when reviewing COFs. Completed a year-long leadership development program in 2016. Co-authored 12 peer-reviewed scientific papers. Served as project manager for the Food Safety Modernization Act Risk Profile-organized; edited and provided research for the document.

Regulatory Review Officer, (O-4 billet) 01/2007 - 06/2011
5100 Paint Branch Parkway, College Park, MD 20740 United States

Served as a subject matter expert (SME) for the Risk Profile in Raw Milk Cheese Group. As SME drafted several documents on subjects such as the availability and quality of scientific data for pathogens associated with raw milk cheese, and evaluation of the relative risk of human illness from consumption of fresh and soft-ripened cheeses. Drafted a document describing how several pathogens of concern would survive in environments similar to those found during cheese production. Completed several reviews of foreign standards of dairy products submitted to the World Trade Organization (WTO) for potential trade barriers. Served as the Executive Secretary for the Interagency Risk Assessment Consortium (IRAC.) In this role, I co-organized quarterly meetings to promote scientific research and facilitate FDA risk assessments. Presented in Ireland as an invited speaker on the resistance of *Cronobacter sakazakii* to thermal and acid resistance.

Regulatory Research Officer, (O-4 billet) 12/2004 - 01/2007
5100 Paint Branch Parkway, College Park, MD 20740 United States

Served as a subject matter expert (SME) on foodborne pathogen survival. Completed hazard prioritizations documents on several commodities such as: dried milk, ice cream, deli meat, deli salads and cream filled products. Furnished in-depth technical reports, risk profiles and other documents to the Branch Chief and Office Director. These reports included a Filtration Risk Profile of fluid milk- determined based on current scientific literature, determining if the current time and temperature regulation for fluid milk retention would provide adequate safety margins against toxin production in milk and whey contaminated with *Staphylococcus aureus* or *Bacillus cereus*. Researched and wrote the FDA statement on the health concern for informal cheese entries (“Suitcase Cheese” or cheese entering the United States by noncommercial port entry). The document was used as part of the raw milk cheese action plan. Co-authored a proposal on the definition on bovine colostrum for the National Conference on Interstate Milk Shipments (NCMIS), the information was used as a support document for not certifying colostrum under milk and milk products.

Regulatory Research Microbiologist GS: 9-1 to 11-4 08/1998 - 12/2004
5100 Paint Branch Parkway, College Park, MD 20740 United States

Designed and carried out experiments to increase identification of pathogens in foods, and to identify the thermal resistance and acid resistance of foodborne pathogens such as *Enterobacter sakazakii* and *Listeria monocytogenes*. Provided training and technical guidance to student and other laboratory personnel in the proper use and procedures of

laboratory and computer equipment. Assisted in the training of personnel from FERN and LRN laboratories in methods for the isolation and identification of biothreat agents *Yersinia pestis* and *Francisella tularensis* and on the principle and practices of working in Bio Safety Level (BSL)-3 laboratories. Trained to handle biological and chemical spills in the laboratory.

Education:

Johns Hopkins School of Public Health
Baltimore, MD United States

DrPH: expected 08/2018

Major: Environmental Health Science

Courses include: Principles of Environmental and Occupational Hygiene, Public Health Toxicology, Fundamentals of Occupational Health, Environmental and Occupational Health Policy. Have completed all classwork and written comps.

University of Maryland
College Park, MD United States

Master's Degree 12/2003

Major: Food Science

Temple University
Philadelphia, PA United States

Bachelor's Degree 08/1994

Major: Biology

Additional Training:

ASHI Emergency Medical Responder

Active through: June 2019

Northampton Volunteer Firefighter:

1994 – 1998

Trained in Firefighter 1, Basic Vehicle Rescue, Ropes and Rigging and Hazardous Waste Operations and Emergency Response (Hazwoper) training.

Affiliations

Commissioned Officer Association – Member

Member of the Mid Maryland Triathlon Club June 2010-Present

Completed multiple triathlon and road races including an Ironman triathlon (140.6 mile race.)

Professional Publications:

1. Edelson-Mammel, S.G., M.K. Porteous, and R.L. Buchanan. 2006. Acid resistance of twelve strains of *Enterobacter sakazakii*, and the impact of acid habituating the cell to an acidic environment. *Journal of Food Safety*. 71 (6):201-207.

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