Analysis of Benefits and Costs of Radon Reduction Strategies Recommended by the EPA: Cost-Effective Interventions for Lung Cancer Prevention

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Introduction

Radon has long been recognized as the second leading cause, after tobacco use, of lung cancer, which is responsible for more deaths than any other cancer. In 1986, the original *A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon* — jointly issued by the Department of Health and Human Services (HHS) and U.S. Environmental Protection Agency (EPA) — outlined a strategy for controlling risks from in-home radon (USEPA and HHS 1986). The strategy was based on short-term screening measurements, confirmatory measurements in homes with measured levels above 4 picocuries per liter (pCi/L), and mitigation of homes with levels above the "action level" of 4 pCi/L. After the 1986 Citizen's Guide was issued, an EPA technical report (USEPA 1992) described results from a wide range of technical analyses, which greatly broadened our understanding of (1) radon risks, (2) the costs and (3) effectiveness of home mitigation. The report estimated about 13,600 annual lung cancer deaths related to exposures to radon in homes in the United States (total population in 1980 of about 250 million) (Puskin 1992, USEPA 1992). These results were largely based on risk models — derived from epidemiological studies of four cohorts of underground miners — given in the National Academies of Science (NAS), formerly National Research Council (NRC), BEIR IV Report (NRC 1988). The report also included recommendations for refining the EPA's approach to reducing exposure to radon (e.g., to streamline the process for radon testing in homes). The 1994 Report concluded that based on an action level of 4 pCi/L, the cost per life saved would be about $700,000 ($1.4 million in 2023 dollars), which it noted "compares favorably with expenditures the EPA was willing to see incurred for risk reductions in the past." In 2003, the EPA updated its assessment of risk from radon in homes (USEPA 2003) and estimated that of about 157,000 lung cancer deaths in 1995, about 21,000 (13.4%) were related to exposures to radon in homes. The EPA's estimates were calculated using a modified version of one of the risk models recommended in the NRC BEIR VI report (NRC 1999). The BEIR VI risk models were similar in structure to the risk models given in the BEIR IV report but were informed by a richer source of data (e.g., based on data from 11 compared to four underground miner cohorts). Since 2003, important results from pooled analyses of residential case-control studies (e.g., Darby et al. 2005, 2006) have provided direct evidence of risk from radon at levels near the EPA's action level, and most recently, a new pooled analysis of uranium miner study data (Richardson et al. 2022) provides additional insight on radon lung cancer risks. Since the 1994 Report, complimentary information has been made available on the cost and effectiveness of mitigations (e.g., Steck et al. 2012). The EPA has not revised its estimate of the cost per life saved to reflect trends (e.g., in tobacco use) that affect radon-related risks and/or other pertinent new information published after the 1994 Report. The purpose of this report is to compare updated estimates of costs and benefits associated with the EPA's program for reducing radon in homes. The analysis could help policy makers and public health officials determine how to divide limited budgets among different lung cancer prevention initiatives.

Methods

The analysis compares the benefits and costs of programs to test and mitigate existing homes and to build new homes with radon-reducing features. The principal costs associated with radon interventions include radon tests, vent pipes, fans, energy, and labor expenses related to installation, maintenance, and repair. The benefit of radon intervention is the avoided lung cancer cases and includes the avoided cost of lung cancer treatment and the value of the avoided fatalities. It does not include other unquantifiable, but potentially substantial intangible benefits like peace of mind. The benefits and costs of interventions to reduce radon in homes occur over many years. To consistently compare benefits and costs over this long time-horizon, all benefits and costs are discounted to calculate their present value. This analysis examines the net benefit and return on investment for a sample program that tests 2 million homes and mitigates those with elevated radon levels (greater than 4 pCi/L). This analysis also examines the return on investment for a program to build 2 million homes with radon-reducing features and to test and fix such homes with positive test results for elevated radon levels. A discount rate is applied to both costs and benefits. Given the inherent uncertainty in estimating the benefits and costs of efforts to reduce radon exposure, the approach used is a form of a sensitivity analysis; it explores the effect of different data inputs and policy assumptions on the net benefit and return on investment, including alternative risk models, alternative assumptions about effectiveness of radon interventions, and the implications of a lower action level.

Results

The EPA's approach to radon intervention shows positive net benefit under a wide range of assumptions. The radon level in approximately one in 15 homes exceeds the EPA action level (USEPA 1991). A program to randomly test 2 million typical existing homes and mitigate 85 percent of the homes within that group that test above the EPA's action level, according to methods recommended by the EPA, avoids an estimated 3,100–8,000 excess lung cancer deaths over the lifetime of the radon mitigation system**,** with a net present value of $9 billion to $20 billion. This represents a return of $7.38–$15.27 for every dollar invested. For new construction strategies, building 2 million homes over 20 years in high-radon areas with features that reduce radon intrusion, testing the new homes for radon after construction, and installing active soil depressurization in those homes that test above the EPA's action level can avoid an estimated 19,000–48,600 excess lung cancer deaths and have a net present value of $62 billion to $131 billion. This is an estimated return of $25.99–$53.80 per dollar expended. These ranges reflect uncertainty about the risk of radon and the effectiveness of radon intervention. They also reflect the effect of changes to the radon action level. The discount rate also has a significant effect on the results because benefits occur in the future. But the net benefit remains positive even with relatively high discount rates.

Discussion

Radon interventions are straightforward and effective. Testing and mitigation programs and new construction features that reduce radon can significantly reduce lung cancer mortality rates. The findings are robust, and the net benefit remains positive across a range of estimates of risk and other variables. The results obtained by the analysis demonstrate that a radon program at the local, tribal, state, or federal level can provide a significant benefit. The estimate of the net benefit of a program to test 2 million existing homes and to mitigate homes with elevated radon levels assumed that these homes were distributed throughout the country and are in low-, medium- and high-radon areas. The return would be higher if the program focused on 2 million homes in high-radon areas only. Sensitivity analyses show that the intervention efforts are cost-effective even in low-radon areas. The results compare favorably to smoking cessation programs, and a multi-intervention approach that addresses both smoking and radon is likely to be a highly cost-effective way to prevent lung cancer.

Introduction

Radon has long been recognized as the second leading cause of lung cancer, after tobacco use. Lung cancer is responsible for more deaths than any other cancer in the U.S. In 1986, the original *A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon* —jointly issued by the U.S. Department of Health and Human Services (HHS) and the U.S. Environmental Protection Agency (EPA)—outlined a strategy for controlling risks from in-home radon (USEPA and HHS 1986). The strategy was based on short-term screening measurements, confirmatory measurements in homes with short-term screening measured levels above 4 picocuries per liter (pCi/L), and mitigation of homes with levels above the "action level" of 4 pCi/L. Modifications to the 1986 recommended protocol were made in subsequent versions of the Citizen's Guide, but the essential components of the strategy remain unchanged—to test for radon and address measured radon levels above 4 pCi/L.

The purpose of this report is to compare estimates of benefits and costs associated with a program for reducing radon in homes. The analysis evaluates recent data and risk models and incorporates recent demographic data, including the prevalence of smoking. It evaluates the cost-effectiveness of radon interventions and explores the implications of recent risk assessments and other factors on the return on investment in radon interventions. The results can help inform policy makers' decisions about lung cancer prevention measures. The benefits of radon intervention include the avoided radon-attributable lung cancer cases. Non-tangible or -quantifiable benefits are not included but could be substantial. The costs of radon testing and radon mitigation of existing homes and of radon-reducing features in new homes include testing kits, vent pipes, fans, electricity, and labor expenses.

The number of avoided lung cancer cases attributable to a program for reducing radon in homes was estimated using risk models for calculating the number of cases per unit of exposure to radon, estimates of average radon levels, and information on effectiveness in radon reduction strategies in reducing exposure levels. Risk models for estimating radon-attributable lung cancer burden associated with exposure to radon in homes rely on information derived from epidemiological studies of the association between radon exposure and lung cancer. The report compares estimated radon risks using three pooled analyses of epidemiological studies:

1. *The Health Effects of Radon: BEIR VI*. The sixth in a series of studies called the Biological Effects of Ionizing Radiation (BEIR), this study included 11 underground miner cohorts (NRC 1999).
2. *Lung Cancer and Radon: Pooled Analysis of Uranium Miners Hired in 1960 or Later.* This study included uranium miners hired in 1960 or later in the United States and Europe (Richardson et al. 2022).
3. European residential case-control studies (Darby et al. 2005, 2006).

Each relies on different data, but some of the data sets between models overlap. Many of the models rely on data from miners who were exposed to high radon concentrations while mining for uranium, but the Darby et al. (2005, 2006) model used only residential studies in which exposure was at much lower concentrations than in studies based on occupational exposures. Data from Darby et al. provide direct evidence of risk from radon at levels that are of concern for this analysis.

Additional studies were considered; however, these three studies were selected because they best demonstrated the potential variability in the estimates of radon risk, with other studies yielding risk estimates that generally fall within the range of these three studies. The EPA's most recent risk assessment of radon in homes (USEPA 2003) is based on a slightly modified version of a risk model recommended in the BEIR VI report and is referred to as the EPA scaled BEIR VI model. The Pooled Uranium Miner Analysis (PUMA) study, a culmination of the efforts that led to BEIR VI, is the largest pooled study of male underground uranium miners. The pooled analysis of European case-control residential radon studies provides direct evidence (i.e., involving in-home exposures versus exposure in underground mines) of increased risk from radon in homes.

This report also provides a summary of the new risk information and estimates of benefits and costs of radon reduction efforts. To address uncertainty, the analysis compares the benefits and costs of radon reduction efforts under several scenarios varying assumptions about risk, average radon levels, action levels, and the effectiveness of radon reduction efforts. The value of future benefits and costs are discounted to estimate their present value. The analysis also explores the effects of alternative discount rates on the results.

The results from this analysis could help tribal, state or local agencies invest in lung cancer prevention initiatives. The analysis shows radon reduction programs can substantially reduce the risk of lung cancer. A targeted program that reaches the homes with the highest radon concentrations may be the most cost-effective way to reduce the risks from radon exposure for the greatest number of people.

Approach and Assumptions

This section provides a brief overview of the approach and assumptions used to estimate the benefits and costs of interventions to reduce exposure to radon in residences. Please see the appendices for additional details.

Overview of the Approach

Radon is a gas that readily escapes from the soil or rock where it is generated and enters surrounding water or air. Radon infiltration from soil into buildings may result in inhalation exposure. When inhaled, the radiation can damage the cells lining the airways, leading ultimately to cancer. Radon intervention programs test for radon in existing homes and mitigate radon through active soil depressurization (ASD) and other measures when radon is present. Typically, ASD requires a vent pipe in the basement or crawlspace and a fan connected to the pipe that creates negative air pressure, drawing radon from beneath the building into a pipe that exhausts near the roofline. Cracks and other openings in the foundation also should be sealed to prevent additional entry points (AARST 2017, USEPA 1993a). Radon interventions also include building new homes in high-radon areas with radon-reducing features. The estimates of the effectiveness of these programs comprise several steps.

1. Estimate the risk of radon exposure in homes.

The most important information concerning the health risks from radon comes from epidemiological studies of underground miners and case-control studies of residential exposures that provide important information about the health risks from radon. Appendix A provides additional details about these studies. In brief, lung cancer mortality is monitored over time in cohort studies and correlated with estimated past radon exposure. The analyses quantify how risk of lung cancer death depends on cumulative exposure to radon, exposure rate, and such factors as time-since-exposure and attained age (i.e., the age at which lung cancer death may occur).

2. Estimate the number of lung cancer deaths attributed to radon.

The EPA uses the three alternative risk models described above with 2010 baseline mortality rates and smoking prevalence estimates (described in Appendix C) to estimate the annual lung cancer deaths attributable to residential radon exposure. The EPA assumes that radon risk increases linearly with exposure. The lifetime risk of lung cancer death attributable to lifetime exposure to 1.25 pCi/L of radon across the three models is between 0.3 percent and 0.8 percent.

3. Estimate radon occurrence and exposure.

The EPA derived the extent of radon exposure from U.S. Geological Survey (USGS) data (USEPA 1993b) and EPA analyses of residential survey data (Cohen et al. 1994; USEPA 1992, 2003). The EPA assumed the pre-mitigation distribution of radon is log-normally distributed with an arithmetic mean of 1.25 pCi/L and a standard deviation of 1.85 pCi/L, based on the data from the EPA's National Residential Radon Survey (NRRS) (USEPA 1991), summarized in Cohen et al. (1994), Marcinowski et al. (1994), and the EPA *Technical Support Document for the 1992 Citizen's Guide to Radon* (USEPA 1992). The EPA also assumed the baseline arithmetic average radon level in high-radon potential areas is log-normally distributed with an arithmetic mean of 2.57 pCi/L and a standard deviation of 2.87 pCi/L, again based on data from the NRRS (USEPA 1991).

4. Characterize efforts to reduce radon exposure in homes.

The EPA recognizes residential exposure as one of the most significant pathways for radon exposure and recommends testing to identify existing homes that have elevated levels of radon. The EPA set the action level for radon at 4.0 pCi/L and recommends that residents mitigate for radon in homes testing at or above the action to reduce exposure and the associated risk of lung cancer. The most common intervention for reducing radon exposure in existing buildings is ASD, also broadly categorized as radon mitigation. The EPA assumes that radon levels in homes with radon concentrations at or above 4.0 pCi/L can be reduced to 1.0 pCi/L or lower with mitigation. In new construction, radon-reducing features include a vapor barrier under the foundation slab; sealing of sump pits, cracks and joints; and a pipe stub in the foundation for a future active soil depressurization system if needed. These features often are referred to as the "low-cost bundle." The home is tested, and if the radon level exceeds the action level, a fan is installed to activate the system. The EPA estimated the cost of efforts to test existing homes and mitigate homes with radon levels that exceed the action level and of building new homes with radon-reducing features.

5. Compare the benefits and costs over time of efforts to reduce exposure in homes.

The EPA evaluated an example radon program to test 2 million existing homes over 20 years and to install ASD in homes with measured radon concentrations above the EPA's radon action level. The EPA also evaluated an example radon program to build 2 million homes with radon-reducing features over 20 years. The EPA uses the value of a statistical life to value the avoided excess lung cancer deaths associated with radon exposure. It estimates the cost of testing homes, the cost of ASD and the other measures used to reduce radon exposure, and the cost of operating and maintaining ASD over the lifetime of the home. The benefits and costs of the effect of these programs are estimated over time, and the totals are discounted to their present value. The net present value is calculated as the difference between the discounted benefits and the discounted costs. The ratio of the discounted benefits to discounted costs is a measure of the return on investment of radon interventions. Appendix B describes the tool used to conduct the analysis.

Key Inputs and Model Assumptions

Baseline data inputs and assumptions for estimates of testing and mitigation interventions are summarized in **Table 1**. For the purposes of this analysis, it was assumed that 100 percent of homes that install ASD replace the equipment on schedule as recommended. The EPA recognizes that some homes with test results that show that radon levels exceed the action level may not get mitigated.

Table 1. Baseline Inputs for Testing and Mitigation of Existing Homes and Including Radon-Reducing Features in New Homes (Dollar Amounts in 2023 Dollars)

Itemized Costs	
Testing, Including Post-Mitigation Tests[1]	$169
Installation of Active Soil Depressurization (ASD)[1]	$1,826
Operating Costs per Year[1]	$206
Fan Replacement Every 10 Years[1]	$476
Warning Device Replacement at Year 37[1]	$151
Lifespan of Interventions (Years)[1]	74
Passive Measures in New Construction	$619
Cost of Initial Test in New Construction	$56
Installing Initial Fan in New Construction	$476
Itemized Benefits	
Avoided Medical Costs[2] per Patient	$143,436
Value of a Statistical Life[3]	$11,184,498
Radon Exposure and Risk Inputs	
Average Number of Persons per Household[4]	2.7
EPA Action Level (pCi/L)	4.0
Post-Mitigation Radon Level (pCi/L)[5]	1.0
Percentage of Homes Above Action Level That Mitigate	85%
Primary Risk Model[6]	BEIR VI Updated Demographics
National Average Radon Level	
Average (pCi/L)[7]	1.25
Standard Deviation (pCi/L)[7]	1.85
High-Radon Potential Radon Level	
Average (pCi/L)[7]	2.57
Standard Deviation (pCi/L)[7]	2.87

Sources:
[1] Ford et al. 1999, HIRL 2019, Marcinowski and Napolitano 1993, USEPA 1992
[2] USEPA 2007
[3] USEPA 2018
[4] U.S. Census Bureau 2019
[5] Steck 2008, Stanley et al 2017
[6] USEPA,2003, NRC 1999
[7] USEPA 1991

Unfortunately, data on the follow-up rate — the percentage of homes that are mitigated after testing above the action level — are unavailable. For this analysis, the EPA assumed that 85 percent of existing homes that test above the action level are mitigated. The assumption that 85 percent of homes that test above the action level are mitigated reflects likely imperfect implementation with any voluntary program. If programs test homes but do not provide sufficient information to residents about the need to mitigate, the follow-up rate may be lower than 85 percent. On the other hand, if programs mitigate homes with test results above the action level, the follow-up rate will be higher than 85 percent. If a program can ensure that all homes that test above the action level were mitigated, both the benefits and costs of the program would increase, but the benefits would increase more than the costs, and the net present value would increase. The sensitivity analysis later in this report explores the effect of this assumption on the net present value and return on investment. For new construction, the EPA assumed that fans are installed in all new homes built with radon-reducing features that test above the action level.

The estimates applied in this analysis are based on the best available data, but some of the information needed is limited. In some cases, the EPA uses default values based on the best available information, and these values can be updated as new information becomes available. They also can be adjusted to evaluate alternative assumptions. The assumptions in **Table 1** are not definitive and the implication of the uncertainty in the estimates is explored through the sensitivity analyses described below. Furthermore, the costs in **Table 1** are averages based on available information. The cost of testing and mitigating homes depends on the characteristic of the home, and factors like heating and cooling can affect both the cost and effectiveness of the interventions.

The three risk models indicate that the majority of lung cancer cases avoided would develop at least 20 years after the intervention, with many cases decades after that. The EPA discounts the future benefits to calculate their present value and compare them to costs. For this report, the EPA used an annual discount rate of 2 percent. Benefits that would occur in 20 years would be discounted approximately 33 percent, using a 2 percent discount rate. Discounting is necessary to account for the "time preferences": all else being equal, a policy that saves a life today is worth more than one that saves a life in 20 years. It also is necessary to ensure the analysis treats benefits and costs consistently.

Sensitivity Analyses

The EPA conducted a series of sensitivity analyses to identify which inputs or assumptions have significant implications for the cost-effectiveness of the intervention program and which assumptions could vary within a reasonable range without substantially changing the bottom line. As already discussed, the benefit-cost analysis evaluated results using three alternative risk models. Alternative assumptions about the post-mitigation radon levels were also evaluated as part of the sensitivity analysis using available data from studies in the field (Steck 2008). The World Health Organization (WHO) sets its reference level for developed countries at 2.7 pCi/L, or 100 Bq/m^3 (WHO 2009). The EPA explores the health and cost trade-offs of both the EPA action level and the WHO /reference level, as well as a hypothetical lower action/reference level of 2.0 pCi/L. The lower action level is used to demonstrate the implications for the analysis; the EPA is not proposing a lower action level. The EPA also analyzed the effect of the average radon levels, the discount rate, and the expected life span of the equipment on the net benefit and return on investment of radon intervention efforts.

Results

Summary of Baseline and Alternative Risk Models

Table 2 summarizes the effects of testing 100,000 homes per year for 20 years and mitigating homes that exceed the action level (referred to as testing and mitigating homes) and building 100,000 radon-resistant new homes per year for 20 years in high-radon areas under three risk models. The table shows the total number of reduced cancer fatalities associated with the intervention and the net present value of the intervention (in billions of 2023 dollars), assuming a 2 percent discount rate.

Table 2. Comparison of EPA Baseline Risk Scenario and Alternative Risk Model Scenarios With a 2 Percent Discount Rate

Risk Scenario	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
EPA Scaled BEIR VI[1]	5,113	$1.40	$14.40	$13.00	$10.08
PUMA[2]	7,989	$1.40	$21.90	$20.40	$15.27
Residential[3]	3,121	$1.40	$10.60	$9.10	$7.38
Build Radon-Resistant New Construction in High-Radon Potential Areas					
EPA Scaled BEIR VI[1]	31,119	$2.50	$87.90	$85.50	$35.53
PUMA[2]	48,625	$2.50	$133.20	$130.70	$53.80
Residential[3]	18,999	$2.50	$64.30	$61.80	$25.99

[1] Based on the EPA scaled BEIR VI model from USEPA (2003)
[2] PUMA, Richardson et al. 2022
[3] Residential Case Control studies in Darby et al. 2005, 2006

The net present value is a measure of the value to society of radon intervention, net of the cost of intervention. When choosing among alternative policies, the option with the highest net present value will provide the greatest net benefit. Return on investment is reported in Table 2 as well, because it allows easy comparisons of programs of different sizes. It is useful for measuring the effect of an investment on the margin (i.e., what is the return of investing one more dollar in radon intervention?). When comparing alternative estimates, the estimate with the highest return on investment will often, but not always, have the highest net present value. Therefore, the benefit-cost tool measures net present value as well as the return on investment, and both are reported here.

The discount rate affects the results because benefits and costs occur in the future. The net present value and the return on investment tend to fall as the discount rate increases. Though the magnitudes of the net present value and return on investment change with the discount rate, the results do not substantially change the conclusion that the interventions are a cost-effective means of reducing lung cancer deaths. The net present value remains positive, and the return on investment remains above $1.00 for every dollar spent at higher discount rates. The sensitivity of the results to the discount rate is described in the Additional Sensitivity Analysis section, below.

Risk Sensitivity: Estimate Based on BEIR VI Risk Model With Updated Demographics and Alternative Risk Models

Using 2010 demographic data and the EPA scaled BEIR VI risk model, an estimated 5,113 excess lung cancer deaths are avoided by testing 2 million homes and mitigating 85 percent of those homes that exceed the EPA action level of 4 pCi/L. Using a 2 percent discount rate, the net present value of the program is $13 billion, with a return on investment of $10.08 for each dollar invested. If the program focused on testing and mitigating 2 million existing homes in high-radon areas, rather than in all areas of the country, the net present value and the return on investment would be even higher.

The value of building radon-reducing features into new construction in high-radon potential areas is even larger than testing and mitigating existing homes, as shown in **Table 2.** An estimated 31,119 excess lung cancer deaths are avoided by building 2 million radon-resistant new homes in high-radon areas. Using a 2 percent discount rate, the net present value of the program is $86 billion, with a return on investment of $35.53 for each dollar invested. The trends are similar to the ones for testing and mitigation of existing homes, but the return is larger for two reasons. First, the potential radon reduction is larger because the homes would be built in high-radon areas. Second, the cost of radon features incorporated during construction is relatively low.

The Richardson et al. (2021) PUMA and the Darby et al. (2005, 2006) residential study models were used to evaluate the effect of alternative risk assumptions in **Table 2**. Using the PUMA risk model and the smoking, mortality, and life expectancy data from 2010, the number of excess deaths avoided by testing 2 million existing homes and mitigating 85 percent of those homes that exceed the action level would be 7,989 for lifetime exposures. The net present value of the intervention would be $20 billion, with a return on investment of $15.27 per dollar invested, using a 2 percent discount rate. Using the PUMA model, the number of excess lung cancer deaths avoided by building 2 million radon-resistant new homes in high-radon areas would be 48,625. The net present value of the intervention would be $131 billion, with a return on investment of $53.80 per dollar invested using a 2 percent discount rate.

The second alternative risk model evaluated was the Darby et al. (2005, 2006) residential case-control studies model, which uses residential data, rather than occupational data. Using this risk model and the smoking, mortality, and life expectancy data from 2010, the avoided number of excess deaths by testing 2 million existing homes and mitigating 85 percent of those homes that exceed the action level would be 3,121 per million people. Using a 2 percent discount rate, the net present value of the program would be $9 billion, with a return on investment of $7.38 per dollar invested. The number of excess lung cancer deaths avoided by building 2 million radon-resistant new homes would be 18,999. The net present value of the intervention would be $62 billion with a return on investment of $25.99 per dollar invested, using a 2 percent discount rate.

As described above, the range of the risk estimates is within a factor of 3. This variation can be attributed to differences between the underlying data and assumptions of each model, which reflect statistical uncertainty, but are remarkably consistent. The variability associated with other parameters can have a larger effect on the measures of the value of the interventions than the risk estimates. For example, as shown in sensitivity analysis below, the differences in the rates of return due to changes in the discount rate are often larger than the differences in the rates of return among the three risk models. Under the alternative risk scenarios, radon interventions in existing homes are estimated to avoid between 3,121 and 7,989 excess lung cancer deaths and yield a positive return on investment. Building new homes in high-radon areas with radon-reducing features is estimated to avoid between 18,999 and 48,625 excess lung cancer deaths and yield an even greater value.

Average Post-Mitigation Radon Level

The EPA assumes the baseline post-mitigation radon level is 1.0 pCi/L. If interventions are more effective and the post-mitigation level is the 0.8 pCi/L average found in the Steck (2008) study (**Table 3**), the value of testing and mitigating 2 million homes increases from $13 billion to $14 billion using a 2 percent discount rate under the baseline risk scenario. When the lower post-mitigation level is used, the range of the net present value of the program to test and mitigate existing homes expands from$10 billion to $22 billion across the three risk models. The net present value of building 2 million radon-resistant homes in high-radon areas increases from $86 billion to $93 billion using a 2 percent discount rate under the baseline risk scenario. The net present value is between $67 billion and $142 billion, across the three risk models.

Table 3. Comparison of EPA Baseline Risk Scenario and Alternative Risk Model Scenarios Assuming a 0.8 pCi/L Post-Intervention Level With a 2 Percent Discount Rate

Risk Scenario	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
EPA Scaled BEIR VI[1]	5,351	$1.40	$15.10	$13.70	$10.55
PUMA[2]	8,361	$1.40	$22.90	$21.50	$15.98
Residential[3]	3,267	$1.40	$11.10	$9.60	$7.72
Build Radon-Resistant New Construction in High-Radon Potential Areas					
EPA Scaled BEIR VI[1]	33,829	$2.50	$95.60	$93.10	$38.62
PUMA[2]	52,858	$2.50	$144.80	$142.30	$58.49
Residential[3]	20,653	$2.50	$69.90	$67.40	$28.25

[1] Based on modified the EPA scaled BEIR VI model from USEPA (2003)
[2] PUMA, Richardson et al. 2022
[3] Residential Case-Control studies in Darby et al. 2005, 2006

Action Level

The EPA set the action level for mitigation at 4.0 pCi/L in 1986 based on the best available data and technology at the time (USEPA 2016a). Although the EPA currently has no policy proposals to lower the action level, the potential effect on the net present value and the return on investment of an action level that is lower than the current level of 4.0 pCi/L was evaluated for two reasons. First, WHO recommends a lower action level of 2.7 pCi/L. Second, improvements in radon measurement technology suggest that post-mitigation levels below 2.0 pCi/L are now both regularly achievable and measurable (Steck 2008). When the net present value and return on investment are using 2.7 pCi/L and 2.0 pCi/L are compared to the current EPA action level of 4.0 using the BEIR VI risk model (Table 4), the net present value increases, but the return on investment decreases. Both the costs and benefits of radon interventions increase as the action level is lowered, as more homes would pay for mitigation and more people would face reduced risks. The return on investment falls because the fraction of additional homes that would test positive and therefore would mitigate would achieve incrementally smaller reductions in radon than homes with radon levels greater than or equal to the current action level of 4.0 pCi/L. More importantly, however, is that the number of lung cancer fatalities avoided increases as the action level is lowered despite the fact that the benefit per dollar spent falls. The value of the additional avoided lung cancer deaths is greater than the cost of the risk reduction, as shown by the increase in the net present value in Table 4.

Table 4. Comparison of EPA Action Level to Lower Action Levels Using the EPA Scaled BEIR VI Risk Model[1] With a 2 Percent Discount Rate

Risk Scenario	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
4.0	5,113	\$1.40	\$14.40	\$13.00	\$10.08
2.7[2]	7,160	\$3.00	\$20.20	\$17.30	\$6.79
2.0	8,436	\$4.40	\$23.80	\$19.40	\$5.42
Build Radon-Resistant New Construction in High-Radon Potential Areas					
4.0	31,119	\$2.50	\$87.90	\$85.50	\$35.53
2.7[2]	34,431	\$4.80	\$97.30	\$92.50	\$20.44
2.0	36,870	\$6.80	\$104.20	\$97.30	\$15.26

[1] USEPA 2003

[2] WHO recommended guideline of 100 becquerels per cubic meter (Bq/m^3)

The effect of the lower action level is similar if we use the PUMA risk model. Table 5 compares the net present value and return on investment with action levels of 2.7 pCi/L and 2.0 pCi/L to the current EPA action level of 4.0 pCi/l using the PUMA risk model. As with the BEIR VI risk model, the net present value is higher using the lower action levels and the return on investment is lower.

Table 5. Comparison of EPA Action Level to Lower Action Levels Using the PUMA Risk Model[1] With a 2 Percent Discount Rate

Risk Scenario	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
4.0	7,989	\$1.40	\$21.90	\$20.40	\$15.27
2.7[2]	11,188	\$3.00	\$30.60	\$27.70	\$10.29
2.0	13,182	\$4.40	\$36.10	\$31.70	\$8.21
Build Radon-Resistant New Construction in High-Radon Potential Areas					
4.0	48,625	\$2.50	\$133.20	\$130.70	\$53.80
2.7[2]	53,799	\$4.80	\$147.30	\$142.60	\$30.96
2.0	57,610	\$6.80	\$157.80	\$150.90	\$23.11

[1] Richardson et al. 2022

[2] WHO recommended guideline of 100 Bq/m^3

Table 6 compares the net present value and return on investment with action levels of 2.7 pCi/L and 2.0 pCi/L to the current EPA action level of 4.0 pCi/l using the Residential Case-Control Studies risk model. The pattern is similar to what we observe using the BEIR VI and PUMA risk models.

Table 6. Comparison of EPA Action Level to Lower Action Levels Using the Residential Case-Control Studies Risk Model[1] With a 2 Percent Discount Rate

Risk Scenario	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
4.0	3,121	$1.40	$10.60	$9.10	$7.38
2.7[2]	4,371	$3.00	$14.80	$11.80	$4.97
2.0	5,150	$4.40	$17.40	$13.00	$3.97
Build Radon-Resistant New Construction in High-Radon Potential Areas					
4.0	18,999	$2.50	$64.30	$61.80	$25.99
2.7[2]	21,020	$4.80	$71.20	$66.40	$14.95
2.0	22,510	$6.80	$76.20	$69.40	$11.16

[1] Residential Case-Control studies in Darby et al. 2005, 2006

[2] WHO recommended guideline of 100 Bq/m^3

Follow-Up and Effectiveness of Interventions

As described above, the estimates of the net present value and return on investment of programs to test existing homes and mitigate homes with radon levels above the action level assumed that 85 percent of homes that test above the action level follow through and mitigate by installing ASD. The results of the analysis are sensitive to this assumption: both benefits and costs increase as more homes with test results above the action level follow through and install ASD. Furthermore, the estimates assume the passive measures reduce radon levels by 50 percent. The more effective the passive measures, the more the benefits will increase. Costs will also decline as fewer homes will need to activate the system by installing fans. Table 7 compares the net present value and return on investment with these assumptions to two alternatives. For existing homes, it compares the current assumption of 85 percent follow-up with 50 percent and 100 percent using the BEIR VI model, the current action level of 4 pCi/L, and a post intervention level of 1 pCi/L. For new construction, it compares the effectiveness of 50 percent with 10 percent and 75 percent.

The results are similar to what we observe using the PUMA and Residential Case-Control Studies risk models, which are shown in Table 8 and Table 9, below. In all cases, the net present value remains positive, and the return on investment is greater than $1.00 per dollar in cost.

Table 7. Comparison of Effectiveness of Interventions Using the EPA Scaled BEIR VI Risk Model[1], an Action Level of 4 pCi/L, and a Post-Intervention Radon Level of 1 pCi/L With a 2 Percent Discount Rate

Effectiveness (Percentage of Homes)[2]	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
50%	3,007	$1.00	$8.50	$7.50	$8.86
85%[3]	5,113	$1.40	$14.40	$13.00	$10.08
100%	6,015	$1.60	$17.00	$15.40	$10.39
Build Radon-Resistant New Construction in High-Radon Potential Areas					
10%	30,430	$3.40	$86.00	$82.60	$25.48
50%[3]	31,119	$2.50	$87.90	$85.50	$35.53
75%	35,907	$1.90	$101.50	$99.60	$54.02

[1] USEPA 2003
[2] In this table, for existing homes, effectiveness measures the percentage of existing homes with test results above the action level that follow-up and install ASD. For new construction, effectiveness measures the passive measures' reduction in radon levels.
[3] Baseline assumption

Table 8. Comparison of Effectiveness of Interventions Using the PUMA Risk Model[1], an Action Level of 4 pCi/L, and a Post-Intervention Radon Level of 1 pCi/L With a 2 Percent Discount Rate

Effectiveness (Percentage of Homes)[2]	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
50%	4,699	$1.00	$12.90	$11.90	$13.42
85%[3]	7,989	$1.40	$21.90	$20.40	$15.27
100%	9,399	$1.60	$25.70	$24.10	$15.74
Build Radon-Resistant New Construction in High-Radon Potential Areas					
10%	47,548	$3.40	$130.20	$126.80	$38.58
50%*	48,625	$2.50	$133.20	$130.70	$53.80
75%	56,106	$1.90	$153.60	$151.80	$81.81

[1] Richardson et al. 2022
[2] In this table, for existing homes, effectiveness measures the percentage of existing homes with test results above the action level that follow-up and install ASD. For new construction, effectiveness measures the passive measures' reduction in radon levels.
[3] Baseline assumption

Table 9. Comparison of Effectiveness of Interventions Using the Residential Case Control Risk Model[1], an Action Level of 4 pCi/L, and a Post-Intervention Radon Level of 1 pCi/L With a 2 Percent Discount Rate

Effectiveness (Percentage of Homes)[2]	Total Number of Reduced Cancer Fatalities With Intervention	A. Present Value of Costs (Billions of Dollars)	B. Present Value of Benefits (Billions of Dollars)	C. Net Present Value (Billions of Dollars, B−A)	D. Return on Investment (B/A)
Test Existing Homes and Mitigate Homes That Exceed the Action Level					
50%	1,836	$1.00	$6.20	$5.30	$6.48
85%[3]	3,121	$1.40	$10.60	$9.10	$7.38
100%	3,672	$1.60	$12.40	$10.80	$7.60
Build Radon-Resistant New Construction in High-Radon Potential Areas					
10%	18,578	$3.40	$62.90	$59.50	$18.64
50%*	18,999	$2.50	$64.30	$61.80	$25.99
75%	21,922	$1.90	$74.20	$72.30	$39.52

[1] Residential Case-Control studies in Darby et al. 2005, 2006.

[2] In this table, for existing homes, effectiveness measures the percentage of existing homes with test results above the action level that follow-up and install ASD. For new construction, effectiveness measures the passive measures' reduction in radon levels.

[3] Baseline assumption

Additional Sensitivity Analyses

The assumptions about average radon levels in homes and the rate used to discount future cost and benefits can have a large effect on the net present value of programs to test and mitigate existing homes and build new homes with radon-reducing features. To analyze the potential effect of these assumptions, the EPA estimated the net present value of efforts to reduce radon using alternative assumptions about the average radon levels and the discount rate. For the analysis, the EPA uses the EPA scaled BEIR VI risk model and the current action level of 4.0 pCi/L and continues to assume radon interventions will reduce radon levels to 1.0 pCi/L. The results using the other risk models and action levels are similar.

Average Radon Levels

The net present value of radon interventions depends directly on the average radon levels in homes prior to the intervention: the lower the average radon level, the lower the net present value. This relationship is shown in **Figure 1**. The figure shows that average radon levels in existing homes must be approximately 0.3 pCi/L for the net present value of a program to test 2 million homes and mitigate homes above the action level to be negative (i.e., below the bold line). For new homes, the average radon levels also would need to be approximately 0.3 pCi/L for the present value of incorporating radon-reducing features in new homes in high radon areas to be negative.

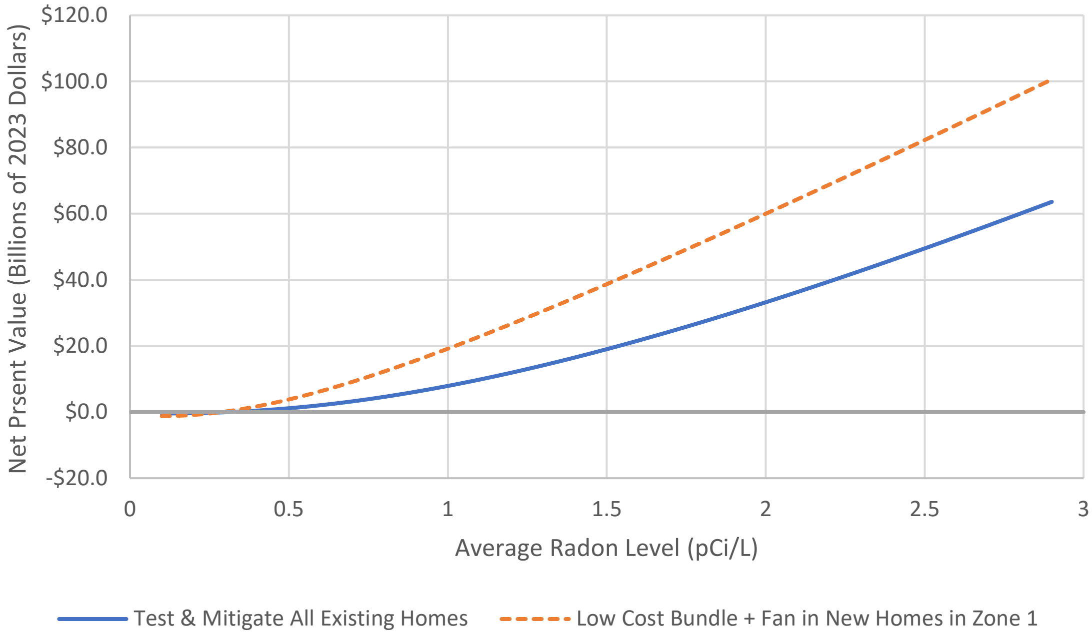

Figure 1. Sensitivity of net present value to average radon levels.

Figure 2 shows the effects of the average radon levels on the return on investment as measured by the total benefit per dollar spent. The benefit per dollar spent is less than $1.00 (shown by the bold line) when the average radon level is less than approximately 0.3 pCi/L.

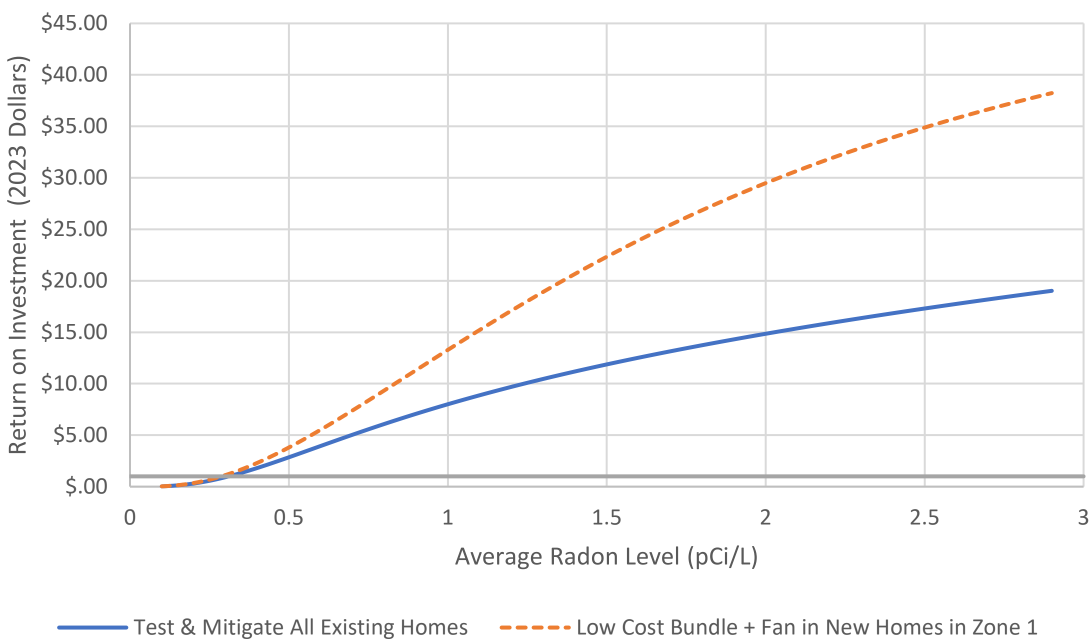

Figure 2. Sensitivity of the return on investment to average radon levels.

Although average radon levels in homes may have declined due to previous interventions, it is implausible that average radon levels are less than 0.3 pCi/L today. Radon intervention remains a cost-effective means of protecting public health.

Sensitivity to the Discount Rate

The results of the analysis are sensitive to the discount rate because the benefits are many years in the future. Despite this sensitivity, radon interventions remain cost-effective over a wide range of discount rates. The EPA calculated the net present value using discount rates of zero (i.e., no discounting of future costs or benefits) to 10 percent. As seen in **Figure 3,** the net present value is positive for efforts to test and mitigate existing homes and to build new homes with radon-reducing features even when the discount rate is 10 percent. The graphs use the EPA scaled BEIR VI risk model and an action level of 4.0 pCi/L. They also assume the post-mitigation level is 1.0 pCi/L. Even if we use the Residential Case-Control Studies risk model, the net present value remains greater than zero when the discount rate is as high as 10 percent.

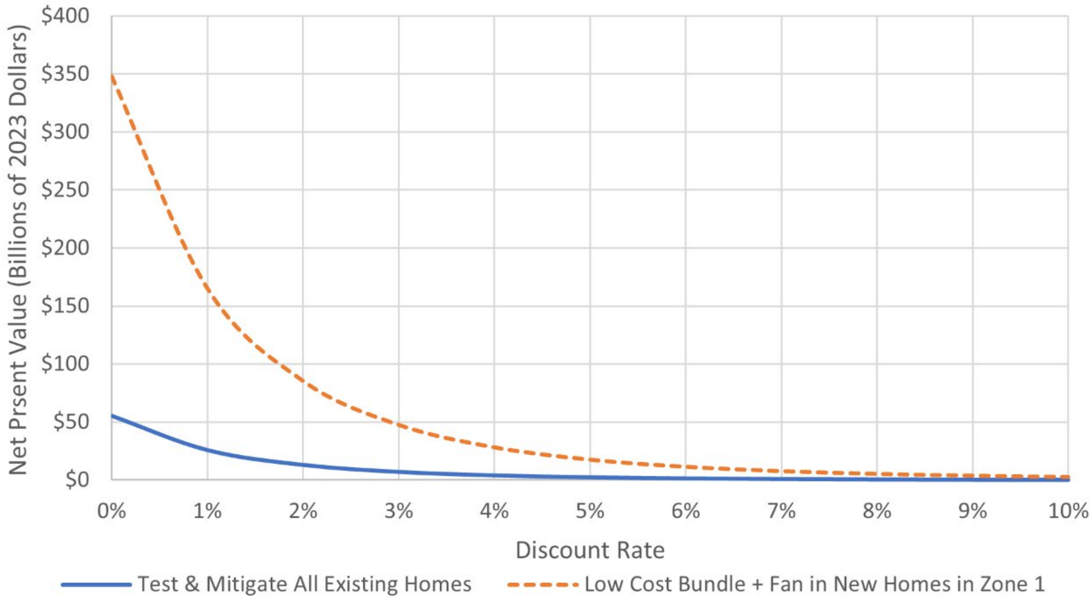

Figure 3. Sensitivity of net present value to the discount rate.

Figure 4 shows the sensitivity of the return on investment to the discount rate. The benefit per dollar spent remains above $1.00 across the range of discount rates.

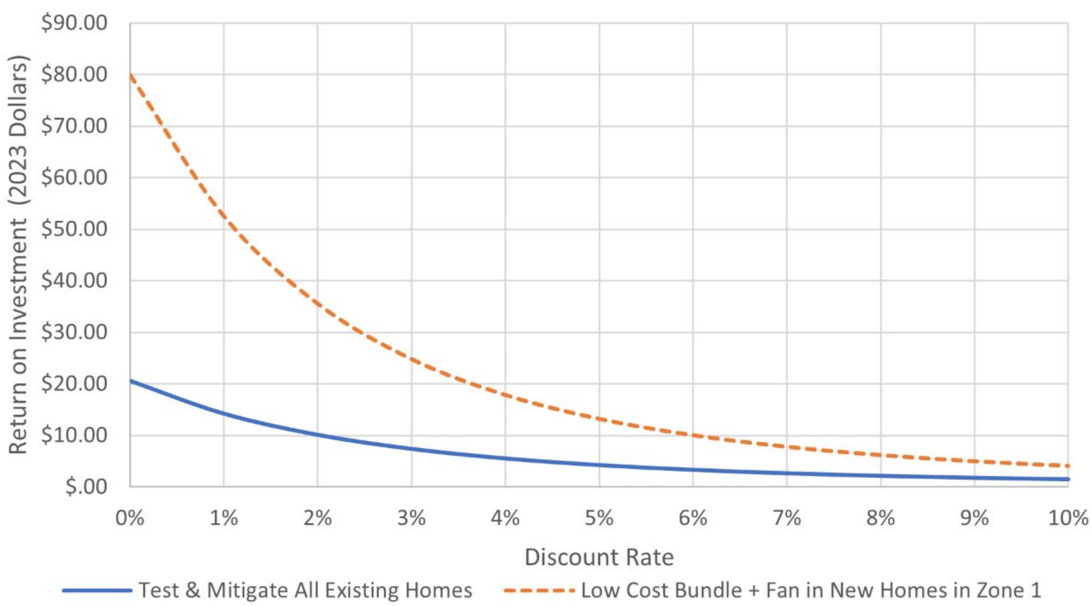

Figure 4. Sensitivity of the return on investment to discount rates.

Sensitivity of the Results to the Expected Life Span of the Intervention

The analysis assumes that the intervention's physical equipment will last 74 years, if properly maintained. The value of the interventions increases as the expected life of the intervention increases, as shown in **Figure 5** and **Figure 6**. The figures are based on the EPA scaled BEIR VI risk model. Results are similar for the other risk models. For the figures, the action level is 4 pCi/L and the post-intervention radon levels are assumed to be 1 pCi/L. The discount rate is 2 percent. Even if the expected life of the intervention is well below 74 years, the net present value remains positive, and the return on investment remains above $1.00.

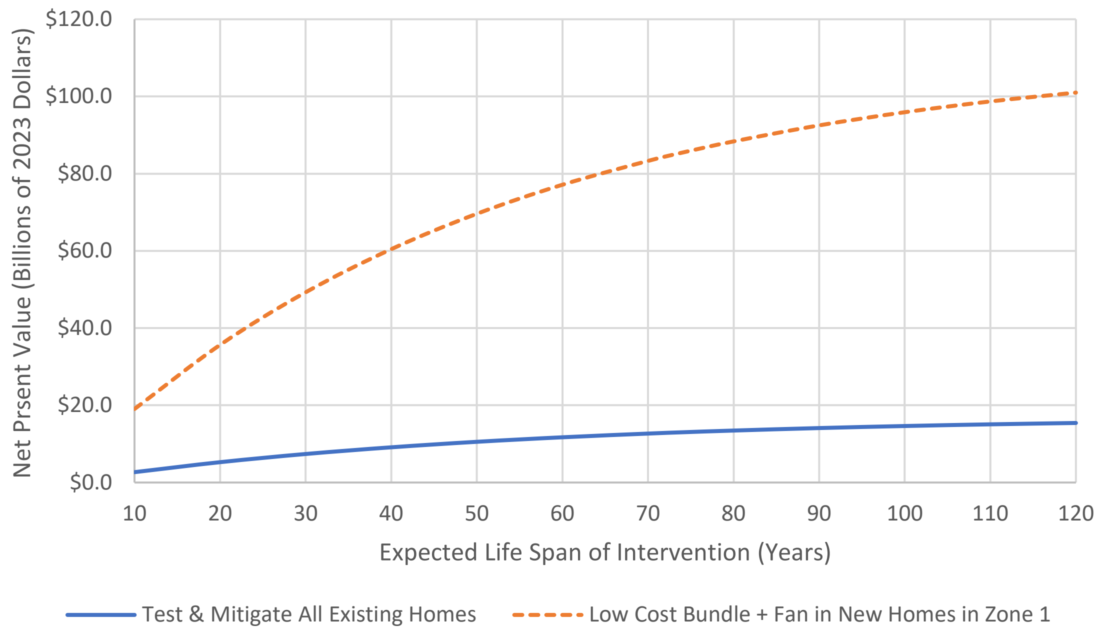

Figure 5. Sensitivity of net present value to the expected life span of the intervention.

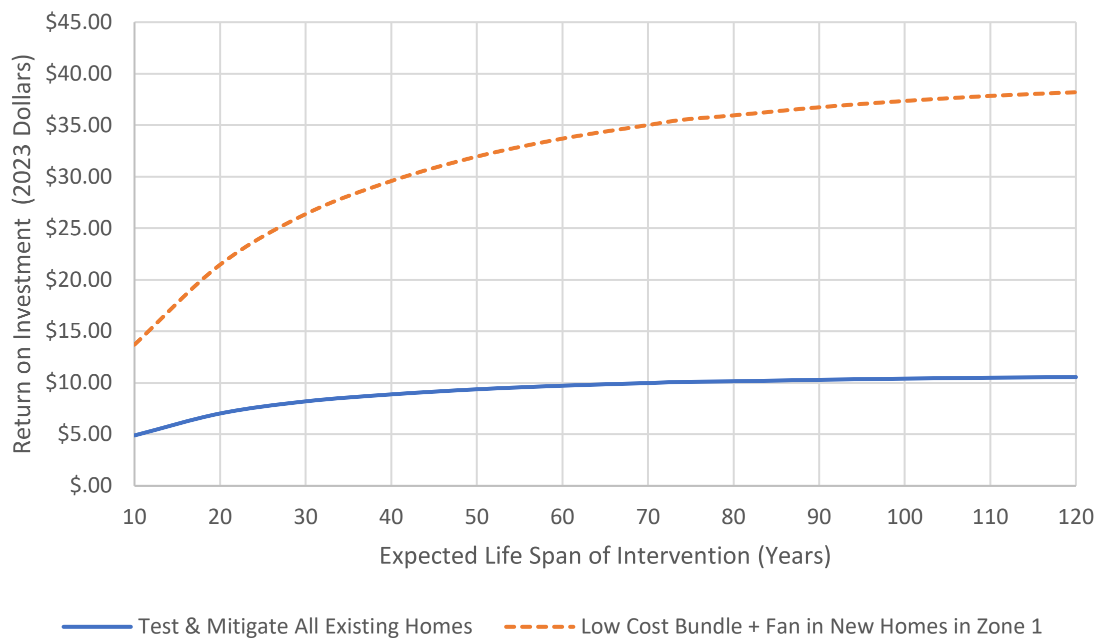

Figure 6. Sensitivity of the return on investment to expected life span of the intervention.

The cost estimates assumes that the ASD system's fans last 10 years and that the residents replace the fan every 10 years. The cost of the testing 2 million existing homes and mitigating 85 percent of the homes within that group that test above the action level and to build 2 million homes with radon-reducing features and to test and fix such homes with positive test results for elevated radon levels will increase if the residents replace the fans more frequently, but the effect is relatively small. This is shown in **Table 10**.

Table 10. Effect of The Life Span of Fans on the Present Value and Return on Investment of Radon Interventions

Frequency of Fan Replacement	Net Present Value (Billions of Dollars)	Return on Investment (B/C)
Test Existing Homes and Mitigate Homes That Exceed the Action Level		
Fans replaced every 10 years	$13.00	$10.08
Fans replaced every 5 years	$12.80	$8.96
Difference	-$0.20	-$1.13
Build Radon-Resistant New Construction in High-Radon Potential Areas		
Fans replaced every 10 years	$85.50	$35.53
Fans replaced every 5 years	$85.20	$32.41
Difference	-$0.20	-$3.11

Discussion

Despite some uncertainty around the costs and effectiveness of certain radon installations, the EPA approach to radon intervention provides a positive net benefit to society within a reasonable range of assumptions about each of these variables. A meta-analysis of the different risk models that measure the relationship between radon exposure and the risk of lung cancer could provide additional insight into the most likely range of values for the excess number of deaths per million people exposed. For the purposes of this analysis, one model with a higher estimate than the primary model and one model with a lower estimate than the primary model were used to establish a range; however, a comprehensive analysis of data that the current models were based on could explore the underlying assumptions in each model and reduce uncertainty.

The results from this analysis could help state, tribal, or local agencies with limited funding determine how to divide budgets among different lung cancer prevention initiatives. The high net benefit for radon reduction programs suggests that a targeted radon reduction program can substantially reduce the risk of lung cancer, even with a small budget. A targeted program that reaches the homes more likely to have the highest radon concentrations may be the most cost-effective way to reduce the risks from radon exposure for the greatest number of people. In addition, regional variations in home and mitigation prices may result in much higher costs in some markets without a corresponding increase in risk reduction.

While the estimates reflect some moderate uncertainty, the value of radon intervention is high under a wide range of realistic scenarios. Smoking remains the leading cause of lung cancer, but radon intervention is an effective approach for reducing the risk of lung cancer and compares favorably with smoking cessation. Numerous studies evaluate smoking interventions, many focusing on cost-effectiveness measures like the incremental cost per additional quit. (See, for example, Levy et al. 2016, Reisinger et al. 2019, Mundt et al. 2023.) A benefit-cost analysis of national and state smoking cessation programs focusing on productivity losses associated with smoking concluded that the return on investment of smoking cessation ranged from $0.86–$2.52 across eight treatment options, including four different types of medical therapies with and without accompanying psychological counseling and accounting for sensitivity to effectiveness of the treatment options (Rumberger et al. 2010). The Centers for Disease Control and Prevention (CDC) evaluated a sustained media campaign to reduce cigarette smoking (Maciosek et al. 2021). Among the campaigns evaluated was a 10-year effort to reduce smoking that cost $6.4 billion. The value of the avoided medical expenses and productivity increases was $10.4 billion, for a return on investment of $1.63 per dollar spent. Radon testing and mitigation in existing homes results in a return on investment of $7.38–$15.98 under the current EPA action level across the three risk scenarios and the two estimated post-mitigation levels, as presented in the results above. Including radon-reducing features in new homes has an even higher return. Both smoking cessation and radon intervention programs are vitally important to reducing morbidity and mortality from lung cancer (HHS 2014). Radon is the leading cause of environmental lung cancer, and smoking is the leading cause of lung cancer overall (CDC 2025). Direct comparisons among these studies are difficult because of different methods used. A full evaluation is beyond the scope of this study, but radon interventions are a potentially cost-effective means of reducing lung cancer deaths that can support smoking cessation programs.

Radon exposure usually is estimated on a national scale using USGS data that measured average radon levels in each county based on samples collected in 1992 (Cohen et al. 1994). County and state studies have been conducted since then, but no data more recent than the 1990s publications exist on a national scale (Marcinowski 1993). The CDC has radon test result data, but these data are based on reported test results and not representative of all homes nationally, including homes that have not been tested. Even though the geological distribution of radon is unlikely to have changed, the housing stock may have changed significantly between 1994 and 2023. The effect of the change in housing stock on residential exposure to radon remains unknown, despite the fact that the building characteristics that are correlated with high indoor radon levels — including basements and crawlspaces — have been investigated (Cohen 1991, Field et al. 1993).

Cost estimates are variable for a few reasons. First, published costs are difficult to obtain; also, every home is different, so every mitigation has a different cost, and costs for radon-specific interventions in new home construction are difficult to differentiate from other construction costs. The cost estimate in this report for an ASD system may not appear as conservative as it could be. Notably, in the scenario where costs of the interventions are two or three times higher than those reported here, the net present value remains positive across the range of inputs.

More research is needed on post-mitigation radon levels in the field. A lower average post-mitigation level would mean that radon intervention has a higher net benefit than assumed in the EPA primary model estimate, and more lung cancer deaths would be avoided. Similarly, a lower action level would eliminate more lung cancer fatalities and would have a higher net benefit. It is important, however, to recognize the net benefit is only one measure of a successful program, and the EPA may revise guidelines based on the health and safety of the public, regardless of cost data, if new research indicates that a lower action level would be beneficial. **Table 11** shows the range of estimates of testing and mitigating existing homes for lower action levels as compared with lower and higher post-mitigation levels using the EPA scaled BEIR VI risk model. The results are similar for the PUMA and residential risk models. The lower action level is used to demonstrate the implications for the analysis; the EPA is not proposing to lower the action level.

Table 11. Action Level as Compared With the Estimated Post-Mitigation Level: Estimated Net Present Value and Return on Investment With a 2 Percent Discount Rate and the EPA Scaled BEIR VI Risk Model

Action Level (pCi/L)	Net Present Value (Billions of Dollars) by Post-Mitigation Radon Level (pCi/L)		Return on Investment by Post-Mitigation Radon Level (pCi/L)	
	1.0*	2.0	1.0*	2.0
1.0	$20.80	$10.20	$3.78	$2.36
2.0	$19.40	$11.70	$5.42	$3.67
2.7	$17.30	$11.50	$6.79	$4.86
3.0	$16.50	$11.40	$7.37	$5.39
4.0†	$13.00	$9.90	$10.08	$7.94

* Current EPA post mitigation level assumption
† Current EPA action level

The post-mitigation levels may be higher than the action level in some scenarios. It is unlikely that the post-mitigation level would exceed the action level, but the table includes those scenarios to show the relative effects of changes in the action level and the post-mitigation level.

In each case, the analysis assumes, on average, each home's radon level is reduced by the intervention. As the post-mitigation level decreases, the return on investment increases. As the action level decreases, the return on investment decreases as homes with lower radon levels are mitigated. Although the benefit per dollar invested may fall, the net present value tends to increase as the action level is lowered, as the value of the additional lung cancer cases avoided exceeds the cost of the additional mitigations. In some cases, the net present value falls; the change in value is sensitive to the discount rate and the post-mitigation radon level. Additional data on exposure and the effectiveness of mitigation are needed to fully evaluate the effect of lowering the action level.

The EPA will continue to promote radon intervention efforts as part of a long-term, comprehensive strategy to prevent radon-induced lung cancer and improve public health. The current program guidelines effectively balance public safety with public costs. As new research emerges, policies and programs may be updated to better serve the public interest.

Appendix A. Detailed Assumptions Used in the Analysis

Scientific Background

The following excerpts from the most recent assessment of risks from radon in homes (USEPA 2003) describe basic facts about radon-222. Other isotopes of radon — radon-219 (actinon) and radon-220 (thoron) — occur in nature and produce radioactive radon progeny. However, actinon and thoron are believed to pose less of a problem than radon-222. This report focuses only on radon-222 and its progeny.

Radon-222 is a noble gas produced by the radioactive decay of radium-226, which is widely distributed in uranium-containing soils and rocks. The radon readily escapes from the soil or rock where it is generated and enters surrounding water or air. The most important pathway for human exposure is through the permeation of underlying soil gas into buildings, although indoor radon can also come from water, outside air, or building materials containing radium. Radon-222 decays with a half-life of 3.82 days into a series of short-lived radioisotopes collectively referred to as *radon progeny*. Because it is chemically inert, most inhaled radon-222 is rapidly exhaled, whereas inhaled progeny readily deposit in the airways of the lung. Three of these progeny, polonium-218, polonium-214, and polonium-2010 emit alpha-particles. When this happens in the lung, the radiation can damage the cells lining the airways, leading ultimately to cancer. (Nuclear decay of radon decay products also releases energy in the form of beta particles and high energy photons, but the biological damage resulting from these emissions is believed to be small compared to that from alpha particles.)

Radon concentrations in air are commonly expressed in picocuries per liter (pCi/L) in the United States, but elsewhere, they are given in SI units of becquerels per cubic meter (Bq/m^3), where a Bq is 1 nuclear disintegration per second. By definition, 1 picocurie is equal to 0.037 Bq; hence, 1 pCi/L corresponds to 37 Bq/m^3.

Radon progeny concentrations also are commonly expressed in working levels (WL) in the United States. One WL is defined as any combination of short-lived radon progeny in 1 liter of air that results in the ultimate release of 1.3×10^5 million electron volts of alpha energy. If a closed volume is constantly supplied with radon, the concentration of short-lived progeny will increase until an equilibrium is reached where the rate of decay of each progeny will equal that of the radon itself. Under these conditions each pCi/L of radon will give rise to (almost precisely) 0.01 WL. Ordinarily these conditions do not hold; in homes, the *equilibrium fraction* is typically 40 percent (i.e., there will be 0.004 WL of progeny for each pCi/L of radon in air [NRC 1999]).

Cumulative radon progeny exposures are measured in working level months (WLM), a unit devised originally for occupational applications. Exposure is proportional to concentration (WL) and time, with exposure to 1 WL for 170 h being defined as 1 WLM. To convert from residential exposures expressed in pCi/L, the BEIR VI committee assumed that the fraction of time spent indoors is 70 percent. It follows that an indoor radon concentration of 1 pCi/L would on average result in an exposure of 0.144 WLM/y = (1 pCi/L) [(0.7)(0.004) WL/(pCi/L)] (51.6 WLM/WL-y).

There is overwhelming evidence that exposure to radon and its decay products can lead to lung cancer. Since the 1500s, it has been recognized that underground miners in the Erz mountains of eastern Europe were susceptible to high mortality from respiratory disease. In the late 1800s and early 1900s, it was shown that these deaths were due to lung cancer. The finding of high levels of radon in these mines led to the hypothesis that it was responsible for inducing cancer. This conclusion has been confirmed by studies of laboratory animals and results from epidemiological studies.

The next two sections describe some of these epidemiological studies and the risk models that have been derived from them, as well as outline how the risk models are applied to estimate; for example, the number of lung cancer deaths avoided through radon reduction efforts.

Epidemiological Studies for Radon

The most important information concerning the health risks from radon comes from epidemiological studies of underground miners and case-control studies of residential exposures. A brief overview of both types of studies is given in the next two sections.

Risk Models From Underground Miner Studies

In cohort studies of underground miners, lung cancer mortality is monitored over time and correlated with the miners' estimated past radon exposure.

The most recent EPA radon risk assessment (USEPA 2003) was primarily based on an analysis by the BEIR VI committee of results from 11 separate miner cohorts from Australia, Canada, China, the Czech Republic, France, Sweden and the United States. Eight of the 11 cohorts were of uranium miners. In part, because of the large size of the combined studies (with 2,700 cancer deaths among 68,000 miners) and the wide range of exposures (and exposure rates), the Committee was able to quantify how risk of lung cancer death for the underground miners depends on cumulative exposure to radon, exposure rate, and such factors as time-since-exposure and attained age (i.e., the age at which lung cancer death may occur). In the BEIR VI risk models, the excess lung cancer risk (i.e., the increment in lung cancer mortality due to exposure to radon) was found to be proportional to cumulative exposure (WLM) and depend on baseline rates.

Since the BEIR VI report, many of the uranium miner cohorts were updated, and results from a very large German (Wismut) cohort have been published. The latter include, for example, an analysis of the effect of radon exposure on lung cancer death with follow-up through 2003 in which more than 3,000 lung cancer deaths had been observed (Walsh et al. 2010)—greater than the total for the BEIR VI analysis. The Pooled Uranium Miners Analysis (PUMA) (Richardson 2022) combines data from most of the uranium miner cohorts that were analyzed for the BEIR VI report—from Canada, the Czech Republic, France, and the United States. In contrast to BEIR VI, it also includes the German Wismut cohort, but no non-uranium miner cohorts — most notably the large tin miner cohort from China. A strength of the study is its very large size (more than 1,200 lung cancer deaths among almost 58,000 miners). Richardson et al. (2022) included in their analysis only miners employed since 1960, for whom assessments of radon progeny are of higher quality and exposures to radon tend to be at lower levels. This should serve to alleviate issues that are often raised with respect to the use of BEIR VI models for making inferences about risks associated with residential radon exposures. The BEIR VI models had been based on data from many miners who had been exposed to much higher levels of radon than those included in the PUMA dataset.

BEIR VI "Age-Concentration" Model

The BEIR VI committee presented two "preferred" models. One of those models, the BEIR VI "exposure-age-concentration" model, was adapted and modified by the EPA for its 2003 risk assessment. For the age-concentration model, excess relative risk (ERR) — the proportional increase in lung cancer death at age (a) associated with past exposures to radon — is given by the formula:

$$ERR(a, w_{5-14}, w_{15-24}, w_{25+}, s) = \beta(w_{5-14} + \theta_{15-24}w_{15-24} + \theta_{25+}w_{25+})\varphi(a)\omega(s) \quad \text{(Eq. 1)}$$

where: β is the exposure-response parameter (risk coefficient); the exposure windows, w_{5-14}, w_{15-24} and w_{25+}, are the cumulative exposures incurred 5–14 years, 15–24 years and ≥25 years in the past; $\theta_{15-24}$and θ_{25+} represent weights associated with those three "time-since-exposure" (TSE) exposure windows. The function $\varphi(a)$ defines how the ERR depends on the current (attained) age (at which lung cancer death might occur), and $\omega(s)$ defines how ERR depends on past tobacco use (i.e., for BEIR VI whether one is an ever- [ES] or never-smoker [NS]). Values for BEIR VI model parameters are given in the first column of **Table 12**. For the modified BEIR VI model used by the EPA, the slope parameter was scaled down to 0.633 WLM^{-1} to yield estimates approximately midway between those that would be obtained by the age-concentration model and the other preferred BEIR VI model.

PUMA Model

The preferred PUMA model and the BEIR VI exposure-age-concentration model have many of the same features. The PUMA model is an ERR model for which risk of lung cancer death increases linearly with cumulative radon exposure and for which the ERR decreases with attained age. However, it differs from the BEIR VI model in that ERR was found to depend on age-at-exposure (ERR per WLM tends to be greater for exposure occurring after age 35 years), but not time-since-exposure (other than there is a minimum 5-year lag that defines the time point after which risks from exposure are elevated). Information was insufficient to draw conclusions on whether ERR for exposure to radon is modified by smoking status. For the PUMA model, ERR is given by the formula:

$$ERR(a, w_{5+,AE<35}, w_{5+,AE\geq 35}) = \beta(\rho\, w_{5+,AE<35} + w_{5+,AE\geq 35})\varphi(a) \quad \text{(Eq. 2)}$$

where: β is the exposure-response parameter (risk coefficient) and $\varphi(a)$ are defined as above for the BEIR VI model; $w_{5+,AE<35}$, is the cumulative exposure after a 5-year lag for ages at exposure < 35, $w_{5+,AE\geq 35}$ is the same for exposures that occur at ages ≥ 35; and the parameter ρ is the relative weight given to exposures occurring before age 35. Values for the PUMA model parameters are given in the second column of **Table 12**.

Risk Models From Residential Case-Control Studies

Since the BEIR VI (NRC 1999) and the EPA 2003 technical report on radon in homes, results from several epidemiological residential case-control studies have been published. A case-control study is one in which individuals with the studied outcome (e.g., lung cancer) and individuals without the outcome are identified and compared with respect to a supposed causal attribute. In the residential case-control studies, measurements of radon were taken in current and past residences for these individuals — typically over periods extending back 30–35 years. Results from these studies are particularly important, given, for example, that exposure rates in many of the BEIR VI miner studies were often orders of magnitude greater than those of most concern in homes (e.g., at about the action level of 4 pCi/L). A problem with these residential studies—stemming in part from the relatively low exposures typical from in-home radon — is that individual studies lack statistical power for detecting risk from exposure to radon. To address this issue, "pooling" efforts were undertaken to combine information from residential case-control studies in Europe, North America, and China. The risk model derived from the largest of these pooled analyses — of the European studies — was chosen for this cost-benefit analysis. The pooled analysis of the European residential case-control studies (Darby et al. 2005, 2006) provided direct compelling evidence of an excess risk from residential exposure radon; there was a statistically significant dose-response relationship even at levels near the action level of 4 pCi/L.

Pooled European Residential Case-Control Studies Model

The ERR model fit to the European residential case-control studies is the simplest of the three alternative risk models used for this benefit-cost analysis. Results suggested a linear increase in ERR with cumulative exposure incurred within 5–35 years in the past, but little or no evidence that ERR is modified by smoking status, sex, or age. For this model, ERR is given by the simple formula:

$$ERR(w_{5-34}) = \beta w_{5-34} \qquad \text{(Eq. 3)}$$

where: β is the exposure-response parameter (risk coefficient), and w_{5-34}, is the cumulative exposure that occurred 5–34 years in the past. The model is summarized in the third column of **Table 12**.

Application of Radon Risk Models for Calculating Risk From Radon in Homes

The three models are relatively easy to apply to calculate reductions in lung cancer death rates that would be expected from interventions that lower radon levels. The methodology is illustrated here using the BEIR VI model.

Suppose that in the year 2000, radon mitigation of homes results in average decreased radon levels in those homes of 5 pCi/L. Given that a radon level of 1 pCi/L corresponds to an annual exposure of 0.144 WLM, at 5 pCi/L, the annual reduction in exposure would be five times that or 0.72 WLM. Then to calculate the reduction in lung cancer death rates for 60 year NS inhabitants of the mitigated homes in 2040, we have: a=60, w_{5-14} = 7.2 WLM (exposure reduced by 0.72 WLM per year for the 10 years from 2025 through 2034), w_{15-24} = 7.2 WLM (for the 10 years of reduced exposure from 2015 through 2024, and w_{25+}= 10.8 WLM (for the 15 years for the reduced exposure from 2000 through 2014). Equation 1 is then applied, yielding an estimated reduction in the ERR for lung cancer death rate at age 70 equal to:

$$ERR(70, 7.2WLM, 7.2WLM, 10.8\ WLM, NS)$$
$$= 0.0768((7.2 + 0.78(7.2) + 0.51(10.8))(0.29)(2) = 0.816.$$

Suppose the baseline lung cancer death rate among NS males in 2040 will be 3 per 10,000 (i.e., the expected annual number of lung cancer deaths would be 30 in a population of 100,000 male NS of age 70 years). The baseline assumes average radon exposure. Then a reduction in radon levels by an average 5 pCi/L over a 40-year period would reduce the lung cancer deaths (among those 70-year-old men) during the next (41st) year to about 0.816(30) or about 24.

The calculations are easily generalized to estimate the number of lung cancer deaths that would be avoided (in a specific year) through radon mitigation in populations of all ages. To illustrate, suppose there is another population of $N_{male,NS}$ =10 million NS males (of all ages) and that (as is often the case), the number of people of a specific age (a) is approximately proportional to the probability of surviving to that age ($S(a)$). Then, in this population, the number of males of age (a) is:

$$N_{male,NS}(a) \approx N_{male,NS} \frac{S_{male,NS}(a)}{\sum_{x=0}^{120} S_{male,NS}(x)} \qquad \text{(Eq. 4)}$$

Then, the age-specific number of deaths avoided in a year (denoted as $B^*(a)$) can be approximated by:

$$B^*_{male,NS}(a) = N_{male,NS}(a) ERR(a, w_{5-14}, w_{15-24}, w_{25+}, s) h_{male,NS}(a) \qquad \text{(Eq. 5)}$$

where $h_{male,NS}(a)$ is the baseline lung cancer rate (for the population of NS) at age a. Then, the total number of deaths avoided (in a specific year for people of all ages) is:

$$B^*_{male,NS} \approx \sum_{x=0}^{120} B^*_{male,NS}(x) \qquad \text{(Eq. 6)}$$

It is also useful to obtain per capita values for estimated lives saved (risk avoided) by dividing the estimated total number of lives saved each year (e.g., $B^*_{male,NS}$) by the respective population numbers, as in equation 7.

$$R_{male,NS} = B^*_{male,NS}/N_{male,NS} \qquad \text{(Eq. 7)}$$

Note that equations 4–6 above are approximations; the actual formulas used to estimate deaths avoided are based on slightly different formulas (based on the trapezoidal rule). The same approach was used to calculate deaths avoided for other populations (e.g., female ES).

Finally, to estimate risks for a population that includes NS and ES of both sexes, we assume that the total numbers for the four sex-smoking-specific subpopulations are approximately proportional to the products of the subpopulation-specific life-expectancies times annual number of births. Let

$N = N_{male,NS} + N_{female,NS} + N_{male,ES} + N_{female,ES}$

$p_{male,ES}$ denote the proportion of baby boys that will eventually smoke (be ES)

$p_{female,ES}$ the corresponding proportion for baby girls

$LE_{male,NS}$ denote the life expectancy for male NS; $LE_{male,ES} \approx \sum_{x=0}^{120} S_{male,NS}(x)$

$LE_{female,NS}$, $LE_{male,ES}$, $LE_{female,ES}$, $LE_{female,NS}$the corresponding values for the other subpopulations.

Then, assuming also that the sex-ratio (of boys to girls that are born) is 1.05:

$$N_{male,NS} \approx w_{male,NS}N = \frac{1.05*(1-p_{male,ES})*LE_{male,NS}}{D}N \qquad \text{(Eq. 8)}$$

where D (for denominator) is just the sum of the subpopulation-specific "numerators":

$$D = 1.05\big((1 - p_{male,ES})(LE_{male,NS} + p_{male,ES}LE_{male,ES}) + (1 - p_{female,ES})(LE_{female,NS} + p_{female,ES}LE_{female,ES})\big).$$

The number of deaths avoided in a specific year in the entire population (of ES, NS, males and females) is:

$$B^* = N(w_{male,NS}R_{male,NS} + w_{female,NS}R_{female,NS} + w_{male,ES}R_{male,ES} + w_{female,ES}R_{female,ES}) \qquad \text{(Eq. 9)}$$

and by dividing both sides of equation 8 by N,it follows that the per capita risk (B^*/N) for the entire population is a weighted average of subpopulation-specific risks.

Finally, for the calculations of risk for mixed populations of female and male NS and ES (Eq. 8), the EPA assumes that in 2010, $p_{male,ES} = 0.46$ and $p_{female,ES} = 0.34$. These ES prevalence values were based on current data on smoking prevalence for adults (see Appendix C) and the assumption that the proportion of youth (ages < 18) who will be ES can be approximated by the percentage of those of age 18 who have begun smoking.

Estimates of Radon-Induced Lung Cancer Deaths

Using the three alternative risk models described above with 2010 data on mortality, the EPA estimated annual lung cancer deaths attributable to residential radon exposure. Table 12 provides model input parameters for the three relative risk models (BEIR VI, PUMA, and the European pooled residential study). The EPA compared these estimates of radon-attributable lung cancer deaths with those reported in EPA's 2003 report, which estimated that in 1995, about 21,000 radon-associated lung cancer deaths occurred. EPA's 2003 estimate was based on the application of the BEIR VI model to 1990 mortality data (i.e., data on both all-cause and lung cancer mortality rates), an estimate that the average radon level in the United States was 1.25 pCi/L (Marcinowski et al. 1994), and data on the number of lung cancer deaths in 1995. Although the radon data are 30 years old, more-up-to-date household data about residential radon exposure are not available. New construction with radon-reducing features and mitigation of existing housing are changing exposure, but changes will take many years to dramatically change risk.

Table 12. Summary of the Three Alternative Radon Risk Models Used for the Cost-Benefit Analysis

Parameter	EPA Scaled BEIR VI Age-concentration model (NRC 1999)[1,2]	PUMA (Richardson et al. 2022)[3]	Pooled European Residential (Darby et al. 2006)[4]
$\beta \times 100$	7.68 (per WLM)	8.38 (per WLM)	1.37 (per WLM)
Time-since-exposure (θ)			
5-14	1	N/A	1
15-24	0.78	N/A	1
25-34	0.51	N/A	1
≥35	0.51	N/A	0
Attained age (the age at which cancer death may occur) (φ)			
<55	1	1	N/A
55-64	0.57	0.55	N/A
65-74	0.29	0.2	N/A
≥75	0.09	0.14	N/A
Age-at-exposure (ρ)			
<35	N/A	0.59	N/A
≥ 35	N/A	1	N/A
Smoking (ω)			
Never-smoker	2	N/A	N/A
Ever-smoker	0.9	N/A	N/A

[1] In USEPA (2003), a slightly modified version of this BEIR VI model was used. In that report β=0.0633, and the step function for modification by attained-age was smoothed.

[2] For the BEIR VI model, there is no modification in ERR by age-at-exposure.

[3] For the PUMA model, there is no modification by TSE or smoking status.

[4] For the European pooled residential studies model, there is no modification in ERR by attained age, age-at-exposure, or smoking status.

Table 13 shows the probability of premature lung cancer mortality attributable to 1.25 pCi/L radon exposure every year over a lifetime for each model and for never smokers, current smokers, and the general population by gender. These estimates assume life expectancy is 80 years, an average equilibrium fraction of 40 percent between radon and its decay products and an indoor occupancy of 70 percent. These estimates are based on 2010 U.S. smoking prevalence and statistics for lung cancer survival after diagnosis.

Table 13. Lifetime Risk of Lung Cancer Death Attributable to Lifetime Exposure at a Radon Level of 1.25 pCi/L by Gender for Ever-Smokers, Never-Smokers, and the General Population

	Males			Females			Male and Female, Ever- and Never-Smokers
Risk Model	General Population	Ever-Smokers (ES)	Never-Smokers (NS)	General Population	Ever-Smokers (ES)	Never-Smokers (NS)	
EPA Scaled BEIR VI	0.6%	1.1%	0.2%	0.5%	1.1%	0.2%	0.5%
PUMA	0.9%	1.8%	0.2%	0.8%	2.0%	0.2%	0.8%
Residential Case-Control Studies	0.3%	0.7%	0.1%	0.3%	0.8%	0.1%	0.3%

The models were applied to 2010 mortality data to estimate the proportion of lung cancer deaths associated with radon. The estimated number of lung cancer deaths in 2010 attributed to radon for the three models were 12,000, 19,000, and 31,000 per year for the European pooled residential study model, EPA scaled BEIR VI model, and PUMA model, respectively. The central tendency of the distribution of the estimates in this present analysis for 2010 are remarkably consistent with the EPA's 2003 estimate of 21,000 lung cancer deaths per year attributed to radon. Estimates of lifetime risk and radon-attributable burden are subject to considerable uncertainties as discussed in EPA's 2003 report, which were beyond the scope of this work to quantitatively estimate.

The estimated number of lung cancer deaths per million people at a radon exposure rate of 1.25 pCi/L is shown in **Figure 7**, by year since exposure begins, for each of the three models.

Efforts to Reduce Radon in Homes

The EPA recognizes residential exposure as one of the most significant pathways for radon exposure and recommends testing to identify homes that have elevated levels of radon. The EPA action level for radon is set at 4.0 pCi/L. The EPA recommends that homes testing at or above the action level be mitigated for elevated radon levels to reduce exposure and the associated risk of lung cancer and that they be tested again periodically post-mitigation to confirm that radon levels have been successfully lowered and remain lowered.

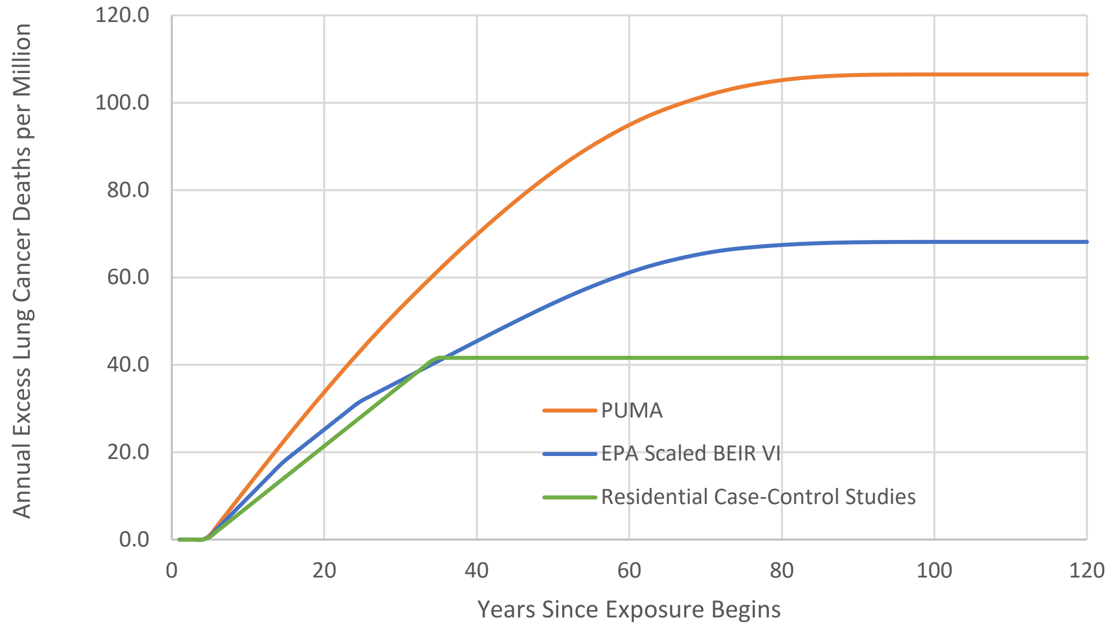

Figure 7. Estimates of annual excess lung cancer deaths per million people from residential radon at a constant radon exposure rate of 1.25 pCi/L using alternative estimates of risk.

The most common intervention for reducing radon exposure in existing buildings is active soil depressurization (ASD), also broadly categorized as radon mitigation. Typically, this technique requires a vent pipe in the basement or crawlspace and a fan connected to the pipe that creates negative air pressure, drawing radon from beneath the building into a pipe that exhausts near the roofline. The EPA assumes that the fan would need to be replaced every 10 years. Cracks and other openings in the foundation also should be sealed to prevent additional entry points (AARST 2017; USEPA 1993a). The EPA assumes that radon levels in homes with radon concentrations at or above 4.0 pCi/L can be reduced to 1.0 pCi/L or lower with mitigation. In previous analyses, the EPA assumed post-mitigation levels of 2.0 pCi/L (USEPA 1992); however, that assumption was based on estimates from the early decades of radon work, and much has been done to change both mitigation and radon testing, tightening the estimate of average post-mitigation radon levels. A study of homes in Minnesota demonstrated that ASD can reduce radon levels to an average of 0.8 pCi/L (Gaskin et al. 2019; Steck 2008, 2012;). This analysis uses 1.0 pCi/L as the baseline post-mitigation estimate and compares the baseline estimate to the 0.8 pCi/L estimate found in the published literature.

In new construction, radon-reducing features include a vapor barrier under the foundation slab; sealing of sump pits, cracks and joints; and a pipe stub in the foundation for a future active soil depressurization system if needed. These features often are referred to as the “low-cost bundle.” The home is tested, and if the radon level exceeds the action level, a fan is installed to activate the system. As with ASD installed in existing homes, the EPA assumes the fan would need to be replaced every 10 years. The cost of testing and mitigation are described in the next section.

Benefit-Cost Analysis Tool

To compare the benefits and costs of efforts to reduce radon levels in U.S. homes, the EPA created a spreadsheet-based benefit-cost analysis tool that evaluates the potential effect of radon interventions on indoor radon exposure. The EPA used the benefit-cost tool to evaluate an example radon program to test 2 million homes over 20 years and to install ASD in homes with measured radon concentrations above the EPA's radon action level. The EPA also used the tool to evaluate an example radon program to build 100,000 homes with radon-reducing features per year over 20 years. The benefits and costs of the effect of these programs are estimated over time, and the totals are discounted to their present value.

The net present value is calculated as the difference between the discounted benefits and the discounted costs. The ratio of the discounted benefits to discounted costs is a measure of the return on investment of radon interventions. The tool is described and illustrated in detail in Appendix B. The appendix includes formulas for net present value and return on investment.

Inputs and Model Assumptions

Baseline data inputs and assumptions for estimates of testing and mitigation interventions are summarized in **Table 1**. For the purposes of this analysis, it was assumed that 100 percent of homes that install ASD replace the equipment on schedule as recommended. The EPA recognizes that some homes with test results that show that radon levels exceed the action level may not get mitigated. Unfortunately, data on the follow-up rate — the percentage of homes that are mitigated after testing above the action level — are unavailable. For this analysis, the EPA assumed that 85 percent of existing homes that test above the action level are mitigated. The assumption that 85 percent of homes that test above the action level are mitigated accounts for a likely imperfect implementation scenario with any voluntary program. If programs test homes but do not provide sufficient information to residents about the need to mitigate, the follow-up rate may be lower than 85 percent. On the other hand, if programs mitigate homes with test results above the action level, the follow-up rate will be higher than 85 percent. If a program can ensure that all homes that test above the action level were mitigated, both the benefits and costs of the program would increase, but the benefits would increase more than the costs, and the net present value would increase. The sensitivity analyses explore the effect of this assumption on the net present value and return on investment.

For new construction, the EPA assumed that fans are installed in all new homes built with radon-reducing features that test above the action level. Results are reported using a 2 percent discount rate. The extent of radon exposure was derived from U.S. Geological Survey (USGS) data (USEPA 1993b) and EPA analyses of residential survey data (Cohen et al. 1994; USEPA 1992, 2003). The EPA assumed the pre-mitigation distribution of radon is log-normally distributed with an arithmetic mean of 1.25 pCi/L and a standard deviation of 1.85 pCi/L, based on the data from the EPA's National Residential Radon Survey (NRRS) (USEPA 1991), summarized in Cohen et al. (1994), Marcinowski et al. (1994), and the EPA *Technical Support Document for the 1992 Citizen's Guide to Radon* (USEPA 1992). The geometric mean is 0.57 pCi/L. A recent study by Stanley (2019) tested 11,727 residential buildings in Canada for radon, finding a geometric mean of 2.92 pCi/L, with 17.8% of homes possessing measured radon greater than or equal to 5.41 pCi/L. Additionally, higher radon concentrations were associated with more recent construction year, greater square footage, fewer stories, greater ceiling height, and reduced window opening behavior. In a related 2017 paper published by Stanley (2017), new homes built after 1992 had radon levels on average 31.5% higher than in older homes. These findings underscore exceptionally high and potentially worsening radon exposure in newer homes. Further evaluation of these study findings and efforts to similarly investigate homes representative of the U.S. residential housing stock are needed.

The estimates applied in this analysis are based on the best available data, but some of the information needed is limited. In some cases, the EPA uses default values based on the best available information, and these values can be updated as new information becomes available. They also can be adjusted to evaluate alternative assumptions. The assumptions in **Table 1** are not definitive and the implication of the uncertainty in the estimates is explored through the sensitivity analyses described in the next section of this appendix and in the body of the report. Furthermore, the costs in **Table 1** are averages based on available information. The cost of testing and mitigating homes depends on the characteristic of the home and factors like heating and cooling can affect both the cost and effectiveness of the interventions.

The inputs and assumptions in **Table 1** are also used to estimate the effects of building radon-resistant homes in high-radon potential areas. The baseline arithmetic average radon level in high-radon potential areas was assumed to be 2.57 pCi/L with a standard deviation of 2.87 pCi/L, again based on data from the NRRS (USEPA 1991). The geometric mean is 1.71 pCi/L. The analysis of the construction of radon-resistant homes uses the same average number of persons per home. It assumes the passive measures reduce radon levels by approximately one-half (Gaskin et al. 2019) and that radon levels will be reduced to 1.0 pCi/L in homes that have fans installed. The cost of testing operating fans used in new construction and replacing them when necessary are the same as the cost associated with fans used for mitigation in existing homes. The risk associated with exposure to radon and the associated benefits for each 1 pCi/L average reduction in radon exposure are the same as with mitigation of existing homes.

The benefits of the programs to reduce radon levels in homes included in the analysis are the avoided excess lung cancer deaths associated with radon exposure. The value of the avoided deaths is calculated by multiplying the predicted number of excess lung cancer deaths avoided through intervention both by the expected cost of lung cancer treatment and by the value of a statistical life (VSL) for avoided deaths, which is based on the EPA's mortality risk valuation (USEPA 2018). The estimated cost of lung cancer treatment is from the *Cost of Illness Handbook* (USEPA 1991) and adjusted for inflation to 2023 dollars using the Consumer Price Index for medical care (BLS 2024b). Most of the benefit of mitigation is from avoided excess lung cancer deaths. Comparatively, the avoided cost of care is relatively small compared to the VSL.

The three risk models indicate that the majority of lung cancer cases avoided would develop at least 20 years after the intervention, with many cases decades after that. The EPA discounts the future benefits to calculate their present value and compare them to costs. For this report, the EPA used an annual discount rate of 2 percent, as recommended in guidance from the Office of Management and Budget (OMB 2023). Benefits that would occur in 20 years would be discounted approximately 33 percent, using a 2 percent discount rate. Discounting is necessary to account for the "time preferences": all else being equal, a policy that saves a life today is worth more than one that saves a life in 20 years. It also is necessary to ensure the analysis treats benefits and costs consistently.

The cost of the radon reduction programs includes the cost of testing the homes, the cost of installing ASD and other radon-reducing features, and the cost of operating and maintaining the equipment over time. The example programs test and mitigate existing homes and build new homes with radon-reducing features over 20 years. The analysis assumes the equipment lasts 74 years, if properly maintained. It assumes fans are replaced every 10 years. Future costs are discounted to calculate their present value. As with benefits, the EPA used a 2 percent discount rate. Costs from the original estimates are adjusted for inflation to 2023 dollars using the Consumer Price Index for all urban consumers (BLS 2024a).

If interventions lower radon levels in a home, the risk of exposure in that unit is reduced for all who live there. More than one family may live in that unit over its useful life, and each family would receive some level of protection compared to families that live in units that have not been mitigated. An implicit assumption is that the rate of exposure of families living in the units is reduced over the time they live in the house. The effect of this assumption about exposure and turnover on estimated benefits is small. The effect of the risk reduction can continue after the intervention stops functioning. (If radon levels are lowered in a home for 10 years, people living in the home will have lower lung cancer risks the rest of their lives.) To ensure the effects of the intervention are captured, the time horizon in the model is 120 years from the intervention (the modeled effects beyond 120 years are negligible). The analysis assumes that costs and benefits are accounted for at the end of each year.

The EPA recommends all homes be tested for radon and homes found at or above the action level of 4 pCi/L be mitigated. Risk is assumed to be linearly associated with exposure; thus, further risk reduction would occur when homes with levels between 2 pCi/L and 4 pCi/L also are mitigated. The EPA recommends a few different testing protocols, as well as the need for additional testing during the life of the home and mitigation system, which are described in the EPA's *A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon* (USEPA 2016a) and in more technical terms in the published accredited standards (AARST 2014, updated in AARST 2023). The EPA also recommends protocols for mitigation and building new homes with radon-reducing features; technical features are found in accredited standards (AARST 2013, 2017; USEPA 2016b).

Cost estimates of radon interventions were derived from previously published radon program cost analyses (Ford 1999, Henschel 1994, HIRL 2019, Marcinowski and Napolitano 1993, USEPA 1992). The costs for radon testing include short-term testing devices and laboratory analyses for both initial tests and post-mitigation tests. The cost of testing assumes that 1.42 percent of homes retest once and that, of those, 91 percent use short-term tests, and the remaining 9 percent use long-term tests (USEPA 1992). The costs for mitigation include the equipment and professional installation of ASD in homes and the cost of operating and maintaining the mitigation system. Operation and maintenance costs were included to account for the cost of electricity needed to run the ASD fan and the cost of replacing the fan equipment every decade. Costs for radon features in new construction include the cost of passive system features, an initial test of the home, installation of the fan for homes that test above the action level, and applicable costs of operating and maintaining the ASD system. All costs presented in this document are in 2023 dollars. Cost data from previous the EPA estimates have been adjusted for inflation (USEPA 1992, 2003). The gross domestic product (commonly known as GDP) price index is used to adjust costs for inflation (BEA, 2024). The cost data are from the 1990s, and if costs grew faster than inflation, the net benefit of radon interventions would be smaller, although the change likely would be relatively small.

The EPA recommends that homes that are mitigated be retested every 2 years (USEPA 2016a). Industry best practices published in MAH-2014: Protocol for Conducting Measurements of Radon and Radon Decay Products in Homes recommend that homes with levels of radon below the action level be retested every five years (AARST 2014). Retesting homes can affect both the costs and the benefits of radon interventions, depending on circumstances. To estimate the potential effect of the retests on the bottom line, additional information is needed about the performance of the mitigation systems, including potential failure rates of fans, and the potential results of the retests. The potential cost of retesting and additional maintenance could be significant, but further research is needed to evaluate it. Therefore, this analysis does not include the cost of additional follow-up tests.

Alternative Assumptions

A series of sensitivity analyses were conducted to identify which inputs or assumptions have significant implications for the cost-effectiveness of the intervention program and which assumptions could vary within a reasonable range without substantially changing the bottom line.

Post-Mitigation Level

The post-mitigation level of 1.0 pCi/L used to establish the baseline mortality could be a conservative estimate. Although data on post-mitigation levels are limited, the baseline EPA estimate of 1.0 pCi/L is conservative when compared to the published literature (Gaskin et al. 2019; Steck 2008, 2012). A study in Minnesota (Steck 2008) found that post-mitigation levels in the field averaged 0.8 pCi/L. Of the homes tested and surveys completed, 40 homes had systems that were older than 2 years, and more than 90 percent of all homes had a living space in the basement. Steck concludes that these results are an improvement from similar studies (Brodhead 1995) done more than a decade prior, which found that radon concentration was lower post-mitigation — 69 percent were below 2 pCi/L — but not as low as the results reported by Steck in 2008. It is possible that improvements in technology and technique can account for this change, but further research would be needed to draw definitive conclusions. Khan et al. (2019) conducted a systematic review of the literature on residential radon interventions worldwide to understand the effectiveness of radon interventions. The study found that most experimental and intervention studies conducted in Europe, Australia, and North America with an active sub-slab soil or sump-depressurization system reduced radon levels up to 99 percent in existing homes that initially had radon levels above reference levels. Stanley et al. (2017) tested 2,382 homes from an area encompassing 82 percent of the southern Alberta population in Canada and found that for 90 homes with an average radon level of 15.5 pCi/L before mitigation, radon mitigation reduced levels to an average of 0.9 pCi/L. Although a conservative assumption of a post-mitigation level of 1.0 pCi/L was used in this study, the studies by Steck et al. (2008) and Stanley et al. (2017) provide additional evidence to support an alternative assumption of an average post-mitigation level below 1 pCi/L. A sensitivity analysis that includes the values found by Steck (2008) was conducted to explore the policy implications of more effective ASD installation.

Action Level

The EPA has set the action level at 4.0 pCi/L based on the best available data about lung cancer risk and previously established best available technology to both test for and reduce radon concentrations. The World Health Organization (WHO) guidelines — which include an analysis of the Darby et al. (2005, 2006) data and other residential studies to model the risk of radon — set a reference level of 2.7 pCi/L, or 100 Bq/m^3. A comparative analysis of the return on investment under different action levels was done between the higher EPA action level, the lower WHO reference level and a hypothetical lower action level of 2.0 pCi/L.

Appendix B. Overview of the EPA Radon Benefit-Cost Analysis Tool

The Radon Benefit-Cost Analysis Tool is a Microsoft Excel workbook that compares the benefits and costs of efforts to reduce radon levels in homes. It contains information about radon occurrence, the risk associated with radon exposure, the cost of radon mitigation and radon-resistant new construction (RRNC), and the monetary value of lowering radon exposure. The Tool uses this information to calculate several measures of the value of efforts to reduce radon exposure in homes. These measures include the following:

- Net present value, or the difference between the discounted present value of costs and benefits.
- Benefit-cost ratio, a measure of the return on investment.
- Cost per lung cancer death avoided.
- Interventions required per lung cancer death avoided.

The Tool requires information about the terms of the analysis — for example, how many homes are to be tested and mitigated — to compare costs and benefits of efforts to reduce radon exposure. Key inputs are identified in the Tool, which contains default values for all inputs. These default values can be updated and revised as new information is developed. **Table 14** summarizes the contents of the Tool.

The model relies on two sets of inputs. The first set identifies the basic assumptions about the terms of the analysis:

- The **discount rate** used to calculate the present value of future costs and benefits.
- The **term** (number of years) to include in the analysis. This is the expected lifespan of the active soil depressurization (ASD) equipment (pipes and fans).
- The **duration** of the effect of the interventions. An intervention today will affect risks for many years. To capture the full effect, the risk models can be extended up to 200 years into the future.
- The timing of the benefits during the year (**payments at start or end of year**) affects the calculation of the present value of future costs and benefits.
- The **base year for prices,** which the Tool uses to present costs and benefits in real rather than nominal dollars.

The second set of inputs characterizes the households and radon occurrence:

- The **average number of persons per household.**
- The **national mean and standard deviation** radon level. The Tool assumes that radon is distributed log-normally, with the mean and standard deviation as provided by the user. The default values are the mean and standard deviation of the homes in the National Residential Radon Survey (NRRS).
- The **mean and standard deviation radon level in Zone 1 homes.** This is used by the Tool to estimate the effect of RRNC in Zone 1. The default values also are derived from the NRRS.
- The average **post-mitigation radon level,** which is an estimate of the effectiveness of ASD.
- The **EPA action level.** The Tool assumes homes install ASD when they test above this level. The default value is the EPA's current action level of 4 pCi/L.

Table 14. The Contents of the Radon Cost-Benefit Analysis Tool

Worksheet Tab Name	Worksheet Tab Contents
Inputs	General inputs required for the analysis, including the discount rate, average radon level and risk model.
Costs	Information on the cost of testing, mitigation and radon-resistant new construction (RRNC).
AvoidedCosts	The cost of lung cancer treatment and the value of a statistical life.
PriceIndices	Price indices to adjust for inflation and convert current dollars to constant dollars.
Mortality	Lifetime mortality data, in tenths of years for 120 years, expressed as excess lung cancer deaths per million people exposed to 1 pCi/L of radon per year.
Risk	Calculated risk of radon exposure based on mortality data.
TestResults	Percentage of homes testing positive for radon, from the Technical Support Document (USEPA 1992).
Impact	Distribution of radon among homes and the calculation of the impact of radon mitigation and RRNC.
RRNC	Distribution of radon among homes pre- and post-passive measures included in RRNC. Results of this tab are used by the Impact tab.
CBA-Mitigation	Comparison of the costs and benefits of future programs to test and mitigate radon.
CBA-RRNC	Comparison of the costs and benefits of future programs to build RRNC.
SummaryTable	Summary table of cost-benefit results.
DiscountRateSensivity	Analysis of the sensitivity of the results to the discount rate.
DurationSensitivity	Analysis of the sensitivity of the results to the duration of the mitigation.
RiskSensitivity	Analysis of the sensitivity of the results to the estimate of radon risk.
RadonSensitivity	Analysis of the sensitivity of the results to the estimate of radon occurrence.
RRNCSensitivity	Analysis of the sensitivity of the results to the percentage of RRNC homes that test positive for radon.
MortalityGraph	Graph of lifetime mortality data.

To evaluate the benefits and costs of efforts to reduce radon exposure, the Tool uses data from several relative risk models. The risk models use data on the dose response from several studies, as well demographic data, including data on the age distribution of the population, the number of men and women, and the number of ever-smokers and never-smokers. The Tool includes risks estimates from seven models:

- EPA Scaled BEIR VI (EPA 2003)
- BEIR VI Concentration (Unscaled) (NRC 1999)
- Wismut (Walsh et al. 2010)
- BEIR IV (NRC 1984)
- Pooled European Residential Radon Model (Darby et al. 2005, 2006)
- Joint European Miner Nested Case-Control Model (Hunter et al. 2013)
- PUMA Primary Risk Model ERR/100 WLM (all-ages; slope factor) (Richardson et al. 2022)

The risk models provide estimates of the number of excess lung cancer deaths associated with exposure to 1 pCi/L of radon by year since the exposure began. The risk is then multiplied by the change in radon exposure due to a given policy to estimate excess lung cancer deaths avoided.

The Tool contains information about the cost of ASD, including installation costs, annual operating costs, and regular maintenance costs. It also includes information about the cost of testing homes and the cost of the passive measures included in RRNC. Costs are adjusted to put them in base year dollars using the gross domestic product (GDP) price index.

The Tool assumes homes will be tested at least one time. Homes tested as part of a real estate transaction are tested once; otherwise, homes are expected to be retested if their initial test result is greater than 4 pCi/L. Some homes will retest using short-term tests, and the rest will retest using long-term tests. The cost of the initial test, the percentage of tests that are real estate tests, the percentage of homes that conduct a short-term retest, and the average costs of the short- and long-term retests are entered by the user. The average cost of testing is calculated and converted to the base year price level. Again, the GDP price index is used to convert prices to the base year.

The benefits of mitigation and RRNC are the avoided costs associated with the treatment of lung cancer and the value of a statistical life (VSL). The expected value of the health care costs incurred to treat lung cancer is from the EPA's *Cost of Illness Handbook* from 1996. It is converted to base-year dollars using the Consumer Price Index for Urban consumers (CPI-U) for medical care. The VSL, used to value the reduction in mortality associated with a reduction in radon exposure, is from the EPA and is in 2006 dollars. It is converted to the base year using the general CPI-U.

Data from the NRRS are used to estimate radon occurrence. The Tool assumes radon is log-normally distributed with a specified mean and standard deviation. The Tool uses this distribution to estimate the proportion of homes that would have radon levels above a given action level. It uses information from the EPA *Technical Support Document for the 1992 Citizen's Guide to Radon* (USEPA 1992) to estimate the number of false-positive and false-negative results to determine the number of homes that will have test results indicating that radon levels exceed the action level in the home. It then uses the distribution to calculate the reduction in radon levels associated with each intervention, calculating an average radon reduction.

The Tool calculates the costs of the intervention and determines when the costs would incur. It then calculates the present value using the discount rate provided by the user. (The default rate is 3 percent.) It calculates the number of lung cancer deaths avoided and when the deaths would have occurred using the risk model selected by the user. It multiplies the number of lung cancer deaths avoided by the average cost of care and the VSL to estimate the dollar value of the benefit in each year. It then calculates the present value of the benefits using the discount rate provided by the user.

The Tool estimates the net present value (NPV) as the difference between the present value of the benefits and the present value of the costs. It calculates the return on investment (ROI) as the ratio of the present value of the benefits and the present value of the costs. It also calculates the cost effectiveness (CE) of the program as the cost per lung cancer deaths avoided, which is the present value of the costs divided by the present value of the avoided lung cancer deaths. (The avoided lung cancer deaths are discounted to ensure they are consistent with the costs.) The following equations show how each is calculated.

1. $NPV = \sum_{t=0}^{T} \frac{E_t(M+V)-H_tC_t}{(1+r)^t}$

2 $$ROI = \frac{\sum_{t=0}^{T}\left(\frac{E_t(M+V)}{(1+r)^t}\right)}{\sum_{t=0}^{T}\left(\frac{H_tC_t}{(1+r)^t}\right)}$$

3. $$CE = \frac{\sum_{t=0}^{T}\left(\frac{H_tC_t}{(1+r)^t}\right)}{\sum_{t=0}^{T}\left(\frac{E_t}{(1+r)^t}\right)}$$

Where:

NPV	=	Net present value
ROI	=	Return on investment
CE	=	Cost effectiveness
E_t	=	Excess lung cancer cases avoided in year *t* by intervention
M	=	Cost of medical care to treat lung cancer cases
V	=	Value of a statistical life
H_t	=	Number of homes with intervention in year *t*
C_t	=	Cost of radon intervention in year *t*
T	=	Number of years included in the analysis
r	=	Discount rate

Finally, the Tool includes several sensitivity analyses:

- *Discount Rate* shows the NPV of the interventions for discount rates of 0 percent to 10 percent.
- *Duration Sensitivity* shows the NPV of interventions for different lifespans of ASD, ranging from 10 years to 120 years.
- *Risk Sensitivity* shows the NPV of interventions for a range of annual risk estimates, expressed as lung cancer deaths per pCi/L of exposure.
- *Radon Sensitivity* shows the NPV of interventions for average radon levels as low as 50 percent of the current estimates to as high as 150 percent of the current estimates.
- *RRNC Sensitivity* shows the NPV and benefit-cost ratio of RRNC (including fan installation in homes that test above the action level) if the percentage of homes that test above the action level is as low as 0 percent or as high as 100 percent.

Appendix C. Data on Baseline Mortality Rates and Smoking Prevalence

Age and sex-specific data on U.S. lung cancer rates for the years 2009–2011 (SEER 2015) were obtained from using the software package SEER-Stat, available from the SEER (Surveillance, Epidemiology, and End Results Program) website.

Data on age-specific lung cancer rates were derived using data available from the National Cancer Institute Cancer Surveillance and Modelling Network (CISNET) website). In brief, age-specific data on lung cancer rates for never-smokers (NS) were based on the fitting of the Two Stage Clonal Expansion (TSCE) model by Meza et al. (2008) to data from two studies: (1) the Nurses' Health Study (for females) and (2) the Health Professionals' Follow-up Studies (for males). TSCE is an example of a biologically based model; it "posits that cells initiated via a Poisson process undergo clonal expansion and malignant conversion via a birth-death-mutation process." (See McCarthy et al., 2012 for further details). McCarthy et al. also provide graphs of the fitted NS lung cancer rates (see Figures 3c and d in that paper). Data on never-smoking prevalence is described in Holford et al. (2014) and was downloaded from the CISNET website. Equation B-1 was used to obtain age and sex-specific estimates of ever-smoker (ES) lung cancer rates (based on the observation that age-specific rates would be weighted averages (with weights dependent on never-smoking prevalence) of age-specific rates for ES and NS:

$$h(a, sex, ES) = \frac{h(a,sex) - p(NS) * h(a,sex,NS)}{p(sex,ES)} \quad \text{(Eq. B-1)}$$

where for ES, $h(a, sex, ES)$ denotes the age- and sex-specific baseline lung cancer death rate and $p(sex, ES)$ is the corresponding (ES) prevalence rate. Similar notation applies for NS, and $h(a, sex)$ is the age- and sex-specific rate for the combined population of ES and NS.

Age and sex-specific survival probabilities for NS and ES were derived using death rate data obtained from the CISNET website. In general, $S(a)$, the probability of survival to age a is:

$$S(a, sex, smoke) = \exp\left(-\int_0^a h^*(x, sex, smoke)dx\right) \quad \text{(Eq. B-2)}$$

where $h^*(x, sex, smoke)$ denotes the smoking and sex-specific) all-cause death rate.

(For NS, the website provided the death rates directly. For ES, the same approach was used as that used to obtain ES lung cancer rates (i.e., substituting all-cause death rates for lung cancer death rates in Eq. B-1).

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