



**COST EFFECTIVENESS OF RESIDENTIAL RADON REMEDIATION WITH
HOUSEHOLD MOBILITY**

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ABSTRACT

The US Environmental Protection Agency (EPA) estimates that exposure to residential radon causes 7,000 to 30,000 lung cancer deaths per year. The EPA has provided extensive technical analysis of and support for their recommended policy response of remediating all homes above a threshold level of radon, but these and other benefit-cost analyses typically do not consider many important dimensions of household heterogeneity, specifically residential mobility. We add to the literature on benefit-cost analysis by using agent based models that allow for heterogeneous benefits. Using this model, we re-examine the EPA's recommendations for radon remediation. Since there is both a capital and an annual cost of radon remediation, many well informed households are better off not complying with the EPA's recommendation. We find that most households are better off by not paying the annual cost of remediation and that only the least mobile households with smokers would undertake the capital cost of radon remediation in houses with very high radon concentrations. Since only a small fraction of the population values radon remediation, our model suggests that approximately 10% of the capital cost is likely to be capitalized into the resale value of the house.

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Abstract

The US Environmental Protection Agency (EPA) estimates that exposure to residential radon causes 7,000 to 30,000 lung cancer deaths per year. The EPA has provided extensive technical analysis of and support for their recommended policy response of remediating all homes above a threshold level of radon, but these and other benefit-cost analyses typically do not consider many important dimensions of household heterogeneity, specifically residential mobility. We add to the literature on benefit-cost analysis by using agent based models that allow for heterogeneous benefits. Using this model, we re-examine the EPA's recommendations for radon remediation. Since there is both a capital and an annual cost of radon remediation, many well informed households are better off not complying with the EPA's recommendation. We find that most households are better off by not paying the annual cost of remediation and that only the least mobile households with smokers would undertake the capital cost of radon remediation in houses with very high radon concentrations. Since only a small fraction of the population values radon remediation, our model suggests that approximately 10% of the capital cost is likely to be capitalized into the resale value of the house.

1 Introduction

The Environmental Protection Agency (EPA) has termed exposure to residential radon "probably the biggest public health problem we have," causing from 7,000 to 30,000 lung cancer deaths per year [1]. Since 1986 the EPA has waged a series of publicity campaigns, urging all householders to test for the presence of radon and to reduce ambient levels of radon when airborne radiation from radon decay products exceeds 4 picoCuries/liter (pCi/l). [4]. If universally adopted, such a program would reduce exposure levels in about 5.7 percent of housing units, occupied by almost 5 percent of the population. The EPA has provided extensive technical analysis of and support for their recommended course of action, including cost-effectiveness analysis [1].

We re-examine the EPA's recommendations using a model that incorporates much of the important heterogeneity in the population. We find universal remediation of all houses with ambient exposure above 4pCi/l (and, possibly, lower levels) would pass a social benefit-cost test. However, we can imagine no conceivable set of circumstances under which there would be anything like general compliance with any action level other than an extremely high one, assuming that people truly understand their individual risk and behave rationally. At 20 pCi/l, for example, an exposure level that is five times the recommended level for remediation, found in less than .01 percent of homes, there would not be universal compliance on the part of well-informed households.

The failure of the voluntary action-level approach arises due to the interaction of two phenomena, either one of which would cause difficulty. First, the remediation technology of choice has both a capital component (sealing, plugging, and installing fans) and an operating component (running and maintaining the fans). Households that do not expect to be in their houses very long generally will not be able to recoup the requisite capital investment unless it is capitalized into the price of the housing unit. (For reasons that we discuss below, we expect capitalization to be much less than 100 percent of the cost.) We estimate that with normal mobility, between 5 and 15% of the initial investment will be capitalized into the house price.

Second, even if operational fans were available in every house that had exposure above any plausible action level, many well-informed households would choose not to operate the fans, reflecting enormous variation in the benefits gained from doing so. The variation in benefits derives from variation in four important characteristics of households: the age, size, and smoking behavior of their members, and their subjective valuation of expected life-years saved. Large households with young smokers will derive relatively large benefits from turning on the fans; small households of elderly nonsmokers will derive essentially no benefit. Because the remediation technology requires that residents operate the system, only the most inconceivably draconian of regulations (someone checking to see that the fans are on) could assure widespread compliance with any action level.

The implication of our analysis is that policy (and the analysis of policy) must be designed to take into account residential mobility, the heterogeneity of the population, and the consequences of radon-remediation technology for individual behavior.

Considering these factors, we conclude that the only way in which general installation of radon-reduction equipment will be undertaken is via government provision or mandatory regulation. We also conclude that, depending on the action level and on the distribution of willingness-to-pay per life-year-saved, a nontrivial fraction of the radon-remediation equipment will not be operated in a given year. Assuming that households are well informed about the risks, however, allowing them to choose whether or not to operate the equipment increases, rather than reduces, the efficiency of policies to deal with the health effects of residential radon.

This paper also adds to the economic literature on willingness to pay for pollution abatement and the capitalization of environmental amenities in housing values. A large literature uses housing market transactions to examine how various pollution abatement policies such as the Clean Air Act [3] and Superfund clean-ups [5]. Generally these studies tend to find small changes in housing values after a relatively large change in environmental quality. In fact, Greenstone and Gallagher find that Superfund clean-ups “are associated with economically small and statistically indistin-

guishable from zero local changes in residential property values [and] property rental rates.” [5]. However, our model suggests that this result may not be particularly surprising if there is a high degree of residential mobility surrounding the clean-up site. Their results may simply reflect a belief on the nearby residents that the health risk from the polluted areas was sufficiently low if the exposure time was sufficiently short. Thus, after the clean-up we would expect to see a change in the rate of housing sales and likely a change in the distribution of ages surrounding a clean-up site.

In the next section we describe the public health and economic models we use to analyze the costs and effects of reducing residential radon exposure. In section 3 we describe the data we use to calibrate our models to estimate the behavior of households. In section 4 we discuss the results and intuition of our simulations and in section 5 we discuss how varying our assumptions affect the outcomes of the model. Finally, section 6 concludes.

2 Model

To evaluate radon-reduction policies we construct a model of individual decisions about radon remediation and mobility. We use an agent based approach where each individual has full information about the health effects of the current level of radon in their house, their complete history of residential radon exposure levels, and their (exogenous) probability of moving out of their current house. Furthermore, we assume at the beginning of the simulation that each agent has done nothing in the past to remediate residential radon in their homes. This is likely similar to the radon exposure history for most of the US population since there has not been a large scale program to encourage households to test their houses for radon and to encourage radon remediation.^{1,2} In the rest of this section we will discuss the model we use to estimate the health effects of radon exposure, then discuss the options that are available to homeowners who want to reduce their radon

¹If some households have installed remediation equipment and then moved, the new occupants would also have to make the active decision to turn the installed fans on.

²If this assumption fails, it only affects each household’s exposure *history* of exposure which is not the driving force in the model.

exposure, and then the economic model of agents' behavior.

2.1 Effect of Radon on Health

Epidemiological studies of underground miners have documented that exposure to high levels of radioactive radon gas can cause lung cancer. The risk of lung cancer from radon can be calculated as a function of cumulative exposure over a person's lifetime. Being exposed to a higher concentration of radon in any year increases that person's chance of developing radon induced lung cancer, though the effect from a radon exposure in a particular year eventually fades over time.

There are strong interactions between radon induced lung cancer and smoking induced lung cancer. People who are current smokers not only are 22 times as likely to develop lung cancer from smoking than non-smokers, they are also approximately six times more likely than non-smokers to develop lung cancer from equivalent levels of radon exposure.

Exposure to residential radon is translated into lung-cancer mortality risk according to the model described by the Commission on the Biological Effects of Ionizing Radiation of the National Academy of Sciences [7]. This model is commonly referred to as BEIR VI.

The BEIR VI model estimates the relative risk that an individual faces for radon exposure based lung cancer as a function of their cumulative radon exposure, age, and if they have ever smoked. The exact model is specified as:

$$RR = 1 + (\Psi_{s=1}s + \Psi_{s=0}(1 - s))(\gamma_1 w_{5-14} + \gamma_2 w_{15-24} + \gamma_3 w_{25+})$$

where RR is the relative risk of lung cancer from radon, s is an indicator equal to 1 for people who were ever smokers, $w_{x_1-x_2} = \sum_{t=x_2}^{t-x_1} w_t$ for radon levels w measured in pCi/l, Ψ is an age and smoking status specific constant and γ_1 , γ_2 and γ_3 are weights used to signify the decreased risk of radon induced lung cancer as the exposure date fades into a person's radon exposure history. Table

1 shows the numeric values for the constants.³

2.2 Remediation Technology

The most prevalent method of remediating residential radon and therefore the only type of radon remediation we consider in this analysis is Active Slab Depressurization (ASD). ASD involves two steps. First, fans are installed in order to ventilate the radon trapped in the area below the foundation slab to the outdoors, while holes in the walls and floors are plugged and sealed. Second, the fans must be turned on, maintained, and occasionally repaired. Running the fans uses electricity and also increases the costs of heating a house [1]. Henschel [6] suggests that over 90 percent of all residential radon remediations use ASD. Initial installation of ASD systems, including testing, plugging and sealing, involves an average cost of \$1200 with a range of \$800-\$2,500.

Running the fans costs an average of about \$125 per year for electricity and increased heating costs.⁴ Annualized maintenance and testing costs, assuming testing every five years, come to another \$24. EPA assumes that the whole system lasts for 74 years, at which time it would have to be replaced. Over the 74-year life of the system, total costs come to \$4,244 discounted at 5%. Note that for any plausible discount rate, the up front costs are small compared to the present value of the operating, testing, and maintenance costs.⁵

Provided that the fans are operating properly, ASD generally reduces radon exposure to an average of 2pCi/l or less, regardless of the initial level of exposure.⁶ (With only a few exceptions,

³There are a few variants of this model described in the BEIR VI report. We use the same coefficient values as the EPA so as to make the analysis comparable.

⁴The EPA estimates a range between \$50 and \$200. CITE - EPA website: <http://www.epa.gov/radon/pubs/consguid.html>

⁵The EPA's Technical Support Document [1] has somewhat higher costs, averaging \$1684 in upfront costs and annual costs of \$150.75. However, \$38.77 of their annual costs is annual radon testing, which we find highly implausible, and many of the more expensive technologies that are averaged into the initial costs are economically dominated by ASD. Moreover, more other work [6] documents that ASD almost always provides high radon reductions, and is almost always the method of choice. Thus, we conduct our analysis under the simplifying assumption that all remediation is done via ASD.

⁶2pCi/l is the average assumed by the EPA in the Technical Support Document [1] and the amount used in this paper as the average exposure for remediated housing units. The "or less" reflects Henschel's remark that ASD "techniques provide high radon reductions, as high as 98 to 99+ percent." [6] Except for a very few houses, such reductions would

this is true of all of the remediation strategies discussed by the EPA [1] and by Henschel [6]). To some extent, the post-remediation level of exposure depends on the characteristics of the house, but only slightly or not at all on the pre-remediation level of exposure.⁷ The implication for cost-effectiveness is straightforward: cost is approximately independent of the level of initial exposure, as is post-remediation exposure. This implies that effectiveness increases almost linearly with the initial level of exposure, so that cost-effectiveness will generally be greater the greater is the initial level of exposure. A given reduction in exposure has the same effect on health no matter what the initial level of exposure, but the higher the initial level, the more reduction can be obtained at a given cost. Note that this does not imply that only high-radon homes are worth remediating. It merely implies that the net payoff to remediation is highest in homes with the highest initial levels of radon.

In the following analyses, we adapt the EPA's conclusion that remediation will reduce exposure to an average of 2 pCi/l to the more analytically tractable assumption that all remediated housing units have exposure levels of exactly 2 pCi/l.

2.3 Behavioral Model

In this section we describe the economic model we use for a household's decision about whether to take action to remediate the ambient radon concentration in their house. Our model allows households to be forward looking about their remediation decisions and allows households to completely understand the health consequences of their decisions.

Since all residents of a particular household are necessarily exposed to the same radon concentrations, our model takes households as the relevant level of analysis. Therefore, we assume

imply post-remediation levels well below 2pCi/l. For our purposes, we accept EPA's estimate of remediation to 2 pCi/l.

⁷See Exhibit F-2 of the EPA's Technical Support Document [1]. The Exhibit shows that the cost of ASD generally varies with technical characteristics of the building foundation, but for all action levels below 20 pCi/l cost does not vary with action level. Above 20 pCi/l, only "Hard to Fix" houses with basements, accounting for 16.5 percent of houses above 20 pCi/l (about 0.6 percent of houses that would be remediated at an action level of 4 pCi/l) cost more than other houses that use ASD, and the difference is \$221.54 of initial cost.

that the household maximizes over all members and that the utility of the household is additive across periods. Thus, a household of two people incur twice the health costs of a household with one individual. More restrictively, we assume that the household has a particular smoking history instead of individuals within the household having a particular smoking history. This means that all adults in a household are current smokers, former smokers, or have never smoked. Moreover, we assume that all households have two members, both of whom are the same age. Due to this assumption we further restrict our model to households with occupants aged 20 or older.

We model household behavior assuming that agents have full information about the health effects of radon exposure according to BEIR VI, the distribution of radon in the current housing stock, the radon level in their current house, and their complete radon history. Households are forward looking with respect to their probabilities of leaving their current house and the likelihood of dying before next period.

At the beginning of each period, a household observes whether or not its current house already has remediation equipment installed, the radon level in their current house, as well as their age, smoking status (current smoker, former smoker, or never smoker), and radon exposure history.

After observing all of this, the household can choose whether or not to install radon remediation equipment in the house and pay the cost of the installation, k , or choose not to remediate the radon. If a household chooses to install remediation equipment or the house already has remediation equipment installed, the agent then chooses whether or not to use the remediation equipment. If the household uses the remediation equipment and pays the associated cost, c , its radon exposure for that period is assumed to be 2 pCi/l. If it chooses not to use the remediation equipment, its radon exposure for that period is the ambient radon concentration in the house. See Figure 1 for a decision tree representing the choices.

The household will move in the next period with some probability, δ . We assume that a household's decision to move is independent of its previous choices of purchasing radon remediation equipment and the concentration of radon in their house. However, if moving is endogenous to

a household's decision to remediate the radon in the house, any investment that has already been made in remediation equipment is a sunk cost and should not influence its decision to move or not in the current period.

We allow our model to take on different values for the probability of moving, δ , and dying, λ , for different types of people. We define types of people, θ , by their age, radon exposure history, and smoking status.

This model leads to two Bellman equations of the form:

$$V_{\theta}^R(r, a, z) = \max\{\text{operate remediation fans, do not operate remediation fans}\} \quad (1)$$

and

$$V_{\theta}^{NR}(r, a, z) = \max\{\text{install remediation, do not install remediation}\} \quad (2)$$

where $V_{\theta}^R(\cdot)$ is the value function for people who already have radon remediation equipment installed in their house and $V_{\theta}^{NR}(\cdot)$ is the value function for people who do not already have remediation equipment installed.

In order to specify what $V_{\theta}^R(\cdot)$ and $V_{\theta}^{NR}(\cdot)$ look like, we will first need to introduce some more notation. Each period (assumed to be a year) households get flow utility, u , from their house and discount the future using discount factor $\beta = 0.95$.⁸ Both residents of each household are the same age, a and have the same smoking histories, s , (current, former, never smokers). We assume that no one begins smoking before age 18 and that the distribution of current, former, and never smokers are the population average for that category at each age. Together, age and smoking status define a type, θ . Each household type, θ , has an exogenous probability of moving each year, δ_{θ} , and a probability of dying during the year, λ_{θ} .

Each household knows the radon concentration of their current house, r , measured in pCi/l, as well as the distribution of radon in the housing stock, $f(r)$.⁹ We then define each household's radon

⁸This discount factor corresponds to roughly a 5.3% discount rate.

⁹The density of radon concentrations (before remediation) in the housing stock can be approximated with a log-

exposure history as a 25×1 column vector, $w = w_a, w_{a-1}, w_{a-t}, \dots, w_{a-25}$, where each entry is the cumulative sum of radon exposure up to time $a - t$. This vector of radon exposure history, w , along with current radon exposure, smoking status, and age determine the increased probability of lung cancer from radon exposure, $h(r, s, a, w)$, from the BEIR VI model described above. Once we multiply the probability of lung cancer by the value of a life-year, we can monetize the risk to the household. This monetized value allows us to calculate if that household finds it worthwhile to install and/or operate radon remediation equipment in its house.¹⁰

We assume that radon remediation equipment has a capital and installation cost, k , and a yearly cost of running the fans and extra heating costs, c . We then define the indicator variable, $f = 1$ if the household chooses to run the remediation fans. With some positive probability, p , if a household changes houses, that house will already have remediation equipment installed in the house. In equilibrium, p will be higher for homes with a higher initial radon concentration, but this doesn't affect households' behavior since we assume households' choose a house independently of the radon concentration.¹¹

Households that have remediation equipment installed will be able to recoup part of their capital expenditures on the remediation equipment through an elevated resale value. One of the important features of our model is that we can estimate both the capitalization of remediation equipment, π , and the probability that a house will have remediation installed, p in an internally consistent

normal density, with mean 1.25 and geometric standard deviation, 3.11; $r \sim \log N(-0.42, 1.13)$. CITE - (Nero 1986)

¹⁰Our central case for the value of a life-year is \$300,000. We do a sensitivity analysis by using life-year values between \$100,000 and \$500,000.

¹¹This is identical to assuming that households do not sort into houses based on the radon concentration. If instead, households perfectly sorted into houses based on radon concentrations, we would not expect to see any capitalization of radon remediation equipment, nor see any remediation equipment installed. The intuition for this is that only those households that have a low cost of radon exposure will move into high radon houses. Some households will have a low cost of radon either because the household is old and will not experience the full effect of the current radon exposure before they die, because it is a non-smoking household and therefore have a smaller health effect of radon exposure, or because it is a young household that is likely to move again soon. If these three groups of households with a low cost of radon exposure are not big enough to inhabit all of the high radon houses we would see some capitalization of remediation equipment. However, the size of the population that falls into one of these three groups far outweighs the number of houses with a high radon concentration. Because we are assuming household are choosing houses independently of radon concentrations, we will overestimate the capitalization of remediation equipment and the fraction of houses that are remediated.

manner so that households make remediation decisions in part based on these parameters. We will describe how we solve for these parameters in Section 2.3.2.

Given this notation, we can define $V_\theta^R(\cdot)$, the value function for households that already have remediation equipment installed as:¹²

$$\begin{aligned}
V_\theta^R(r, a, w) = & \max_{f \in \{0,1\}} u - \underbrace{\left(h(r, s, a, w, E[r', w']) (1 - f) \right)}_{\text{health cost of not running fans}} - \underbrace{h(2, s, a, w, E[r', w']) f}_{\text{health cost of running fans}} - \\
& \underbrace{cf}_{\text{cost of running fans}} + \underbrace{\lambda_\theta (1 - \delta_\theta) \beta V_\theta^R(r, a', w')}_{\text{value of staying in the same house}} + \underbrace{\lambda_\theta \delta_\theta \beta p E_r [V_\theta^R(r', a', w')]}_{\text{value of moving to a house with remediation}} + \\
& \underbrace{\lambda_\theta \delta_\theta \beta (1 - p) E_r [V_\theta^{NR}(r', a', w')]}_{\text{value of moving to a house without remediation}} + \underbrace{(1 - \lambda_\theta)(-\infty)}_{\text{value of dying}} \quad (3)
\end{aligned}$$

and $V_\theta^{NR}(\cdot)$, the value function for households that do not already have remediation equipment installed (either because the household has installed it in a previous period or moved into a house that already had it installed) as:

$$\begin{aligned}
V_\theta^{NR}(r, a, w) = & \max \left\{ \left(u - h(r, s, a, w, E[r', w']) \right) + \underbrace{\lambda_\theta (1 - \delta_\theta) \beta V_\theta^{NR}(r, a', w')}_{\text{value of staying in the same house}} + \right. \\
& \underbrace{\lambda_\theta \delta_\theta \beta p E_r [V_\theta^R(r', a', w')]}_{\text{value of moving to a house with remediation}} + \underbrace{\lambda_\theta \delta_\theta \beta (1 - p) E_r [V_\theta^{NR}(r', a', w')]}_{\text{value of moving to a house without remediation}} + \\
& \left. \underbrace{(1 - \lambda_\theta)(-\infty)}_{\text{value of dying}} \right), \left(\max_{f \in \{0,1\}} u - \left(h(r, s, a, w, E[r', w']) (1 - f) - \right. \right. \\
& \left. \left. h(2, s, a, w, E[r', w']) f \right) - cf - \pi k + \underbrace{\lambda_\theta (1 - \delta_\theta) \beta V_\theta^R(r, a', w')}_{\text{value of staying in the same house}} + \right. \\
& \underbrace{\lambda_\theta \delta_\theta \beta p E_r [V_\theta^R(r', a', w')]}_{\text{value of moving to a house with remediation}} + \underbrace{\lambda_\theta \delta_\theta \beta (1 - p) E_r [V_\theta^{NR}(r', a', w')]}_{\text{value of moving to a house without remediation}} + \\
& \left. \left. \underbrace{(1 - \lambda_\theta)(-\infty)}_{\text{value of dying}} \right) \right\} \quad (4)
\end{aligned}$$

Note that for any variable x , x' is next period's realization of x . The age and smoking specific

¹²We ascribe a utility value of -100,000,000 to each agent if they die. The function of this term is to induce agents into pursuing activities that help them avoid death. Our simulation results are robust to a wide array of negative utility values from dying.

probabilities of moving, δ , and dying, λ , can be found in Table 2 and Figure 2 respectively. Using value function iteration we can solve the system of equations and then find each household's optimal remediation policy function.

2.3.1 Types of Agents

Our model has three dimensions that define each type of agent: age (between 20 and 110, inclusive), smoking status (current, former, and never smokers), and radon exposure history¹³ (including current period unremediated ambient radon level for a total of 26 dimensions). This gives us a total of 28 state variables to integrate over to solve the model.

In order to solve our model we need to give each of our agents a history of radon exposure. We first assign an agent to each radon \times age \times smoking status cells. (This gives us a complete array of types in the $r \times a \times s$ dimensions.) We then impute a history, w_x , for each of these agents conditional on finding the agent in that cell, using age specific probabilities of having moved in the past and the level of radon in the agent's current house.

For instance, consider a 46 year old smoker who is currently living in a house with a radon level of 10 pCi/l. With probability 0.907 they were exposed to that level of radon when they were 45 (and with probability 0.093 had a randomly drawn other radon level). When the agent was 44 they were exposed to a radon level of 10 pCi/l with probability 0.773 ($=0.907 \times 0.852$) from being in the same house, with probability 0.079 ($=0.093 \times 0.852$) were exposed to the radon level from the house they may have moved into when they were 45, with probability 0.134 ($=0.907 \times 0.148$) received a new, random radon draw when they were 44 because they moved that period, and with probability 0.014 received a new, random radon draw when they were both 45 and 44 by moving two years in a row. The number of possible histories grows exponentially with the number of lagged state variables (dimension of w). This gives us a total possible number of types of agents

¹³We use a 50 point grid of evenly spaced radon levels between 0 and 20 pCi/l. We have experimented with increasing the number of grid points to 100 which has very little effect on our results.

of $(\dim(w))^{\text{(grid size)}} \times \dim(\text{age}) \times \dim(\text{smoking status}) \simeq 8 \times 10^{44}$. This is not a computable problem given current computing technology.

The typical solution to this problem is to reduce the number of state variables in the model. However, due to the fact that the BEIR VI model attenuates the effect of cumulative past radon exposure over 25 years and our assumption of persistence of radon concentrations in a household's history, we are not able to condense the number of state variables for the history of radon exposure concentrations, $\dim(w)$.

In order to get around this problem, we sample for the possible histories available in the population and integrate over our subsample of histories (instead of integrating over all possible histories).¹⁴ We have run the simulation with a number of historical types¹⁵ between 100 and 1,000¹⁶ and have found that the results do not seem to be terribly sensitive to the number of historical types. For completeness, we report the results of the simulations we ran for all numbers of historical types. Moreover, if people do not actually know their complete radon exposure history, our simulation is capturing much of the important variation by simply having a high likelihood of the previous few periods of radon exposure correct since most of the 8×10^{44} variations come from the exposure "tree" splitting further in the past.¹⁷

2.3.2 Calculation of the Capitalization Value of Remediation Equipment

In our economic model of households' behavior, both the capitalization of remediation equipment and the probability that an agent moves into a house with remediation equipment already installed are determined endogenously.¹⁸ In order to make these parameters endogenous, after each step in

¹⁴We assume that none of our agents engaged in any radon remediation behavior until the date that the simulation started. Thus our distribution of radon concentrations across agents histories reflect the distribution of radon in an unremediated housing stock.

¹⁵A historical type is a particular moving history for each type (radon \times age \times smoking status \times history). Therefore, for each historical type we are actually solving the dynamic programming problem for $50 \times 91 \times 3 = 13,650$ types.

¹⁶We stop increasing the number of historical types at 1,000 due to computational size since the matrices needed to be held in memory by the computer reach 1.1Gb.

¹⁷Table 3 lists all of the behavioral model parameters with a brief summary of each.

¹⁸In order to ensure that our value function iteration converged in under 1,000 iterations, we rounded the capitalization percent to the third decimal place.

the value function iteration, we calculate the proportion of houses that will have remediation and the probability that each agent will move into that house next period. We assume that agents do not choose houses based on either the ambient radon level or the existence of remediation equipment at a particular house. We do not believe this is a particularly restrictive assumption because the value of other amenities from a particular house are likely to be far greater than the costs of installing remediation fans. Therefore, in the next step of the value function iteration agents have the correct beliefs about these parameters and make their decisions accordingly until we find the fixed point.

3 Data

In order to make our model operational, we use data on age specific death rates, baseline lung cancer rates for current smokers, former smokers, and people who have never smoked.

We also use data from the U.S. Census Bureau on age specific probabilities of moving to inform our model [8]. From the age of 20 until 84, the probability of moving decreases for each age group, from a maximum of 35.5% of 20-24 year olds moving every year to a minimum of 4.3% of 65-84 year olds moving every year, with just a slight increase in the probability of moving for people 85 years old and over. All of the probabilities can be seen in Table 2.

We calibrate our model to match the age distribution in the US by using data from the 2006-2008 American Community Survey [2]. A density plot of this data is shown in Table 3.

4 Results

We present the results of our simulations in Tables 4 and 5. The first line of Table 4 shows the capitalization percentage for each of our simulations, varying both the value of a life-year and the number of household radon exposure histories we consider. As mentioned above, our preferred estimate is from the simulation with 1,000 household radon exposure histories. Within this row,

the capitalization values vary between 5% and 15% depending on the assumed value of a life-year. The literature typically considers a life-year to be worth approximately \$300,000. Under this assumption the capitalization value of remediation equipment is just over 10% with 0.3% of houses having remediation equipment installed in them. To add a little context, if houses with the highest 0.3% of radon concentrations had remediation equipment installed, houses with ambient radon concentrations of 13.4 pCi/l and above would have remediation equipment installed.¹⁹

However, as displayed in Figure 5 we can see there is significant variation in household's remediation decisions based on their age and smoking status. Figure 5 shows a contour plot of the policy functions for a set of agents with the same radon exposure history. Each point on the plot represents an agent with a particular age and current radon exposure, while holding the agent's smoking status and radon exposure history constant. The stalactite-shaped area protruding from the top of the each of the graphs is the boundary between where an agent chooses to install and/or run remediation equipment and fans in their house or not.²⁰ The top row of contour plots show the policy functions for agents who live in houses with remediation equipment already installed, either because they have installed it in a previous period or because the house they live in had it installed when they moved in. The bottom row of contour plots show the policy functions for agents who live in houses that do not already have remediation equipment installed.

We first turn our attention to the bottom row of the contour plots. This row of contour plots show the policy functions for households who live in houses that do not have radon remediation equipment already installed. Thus, if they want to influence the concentration of radon in their house they will need to install the remediation equipment at a cost of \$1,200 and then pay the annual cost of running the fans of approximately \$125.

The stalactite in the two right-most figures delineates the age \times radon concentration combina-

¹⁹A full 7% of the housing stock has a radon concentration above the current EPA recommended action level of 4 pCi/l.

²⁰We also allow for the possibility that an agent would want to install remediation equipment in their house but not pay the variable cost involved with running the fans. Our simulations suggest that this is never an optimal choice for an agent.

tions where households find it worthwhile to install radon remediation equipment and operate it. The size of the stalactite increases as we move from the left picture in the figure to right picture of the figure. This shows that never smokers are least likely to install remediation equipment and/or run the fans and current smokers are the most likely to remediate the radon concentrations in their house. This fits the fact that the largest health benefits of remediation accrue to current and former smokers.²¹

We also see that the very young and very old people tolerate substantially higher radon levels before purchasing or operating radon remediation equipment. These results come from two different sources of variation. The oldest people in our simulation do not install or use radon remediation equipment because there is no health benefit that accrues to them to offset the cost of installation or use. BEIR VI models radon exposure as having no negative health implications until 5 years after the year of exposure. Thus, in the limiting case, 105-110 year olds will never have any adverse health effects of radon exposure since all of our agents are projected to die before they reach 111 years old. This effect attenuates rather rapidly as we examine the optimal policies of agents younger than 105. However, this is the effect that is driving the steep slope of the boundary between the two policies on that side of the contour plot.

On the left side of all of the graphs we see that young people tolerate substantially higher radon levels before purchasing or operating radon remediation equipment. This is due to the fact that young people move frequently and therefore will reap very few benefits from installing remediation equipment. A young person (age 20-24) living in a high radon house has a $\frac{1}{3}$ chance of moving next year whereby they will be living in a house that has an expected radon level of 1.25 pCi/l. Thus, in expectation, they are likely to have a one or two year spike in their radon exposure which will be less detrimental to their health than if they were exposed to that concentration of radon for the next 10 years. However, since the probability of moving falls by over 300% between the

²¹Though the BEIR VI model does not distinguish between current smokers and former smokers, these two groups have different baseline levels of lung cancer. These baseline levels drive the difference in actions between the two groups.

ages of 29 and 45, we also see that the incentive to install and/or operate remediation equipment increases dramatically with age.

Tables 4 and 5 display the trough point for each of contour plots (averaged across all radon history types). We see that the trough generally occurs around the age of 50 with an action level greater than 5 pCi/l depending on the smoking status of the household. These households are the most likely to directly benefit the most from their investment in remediation equipment since they only have a 1 in 10 or 1 in 15 chance of moving in an particular year. Thus, the capitalization value of the remediation equipment plays a substantially smaller role for these households than the younger households. Moreover, these households are likely to live long enough to capture the most of the health benefits of reducing their radon exposure.

We now turn our attention to the top row of contour plots in Figure 5. This row shows the contour plot of the policy functions for households who live in houses that already have remediation equipment installed. This means that in order to decrease the radon concentration in their house, these households only need to pay the cost of operating the fans, approximately \$125. Unsurprisingly, younger households with houses that have lower concentrations of radon operate their fans than if they also needed to install them. In fact, we see that never smokers between the ages of 40 and 60 who have houses with extremely high concentrations of radon find it worthwhile to operate the remediation equipment in contrast to never smokers without equipment already installed.

These simulations all assume that there is no sorting on radon concentrations in the housing market. To the extent that the housing market is efficient at sorting people such that those with the lowest willingness-to-pay for radon reduction (in the extreme, mobile, nonsmoking elderly) tend to find the highest-exposure houses, there would be essentially no capitalization, even at high levels of exposure. Perfect sorting of this kind would also obviate radon exposure as a policy problem, because exposure would do relatively little damage. Even imperfect sorting, which we would expect to see in the housing market, would further reduce capitalization, thereby weakening the incentives for households to install remediation equipment.

5 Discussion of Policy Implications

We have identified two reasons why, if people are well-informed and behave rationally, an EPA-style policy is unworkable. Only one of these – the positive externality associated with installing remediation equipment – is realistically amenable to policy intervention. The second reason is that many households will choose not to operate a remediation system. If people are rational and well-informed as in our model, however, this is not really a policy problem at all, provided that households who would derive net benefits from operating radon remediation equipment live in residences that have remediation installed. The reason for this is straightforward: if well-informed households choose not to operate remediation systems, there is no market failure; we can infer that operating the systems would not be cost-beneficial.

There is no public (and virtually no private) health problem if a household consisting of elderly nonsmokers chooses not to operate the fans. Given any household's value of a life-year, if cost per life year saved in that household exceeds its value, economic efficiency is enhanced when the (well-informed) household chooses not to run the fan. The marginal savings exceed the marginal benefit. Thus the public health problem presented by residential radon involves inducing the installation (and repair) of ASD systems, not the operation of such systems.

Of course, if households are in some combination irrational or ill-informed, this straightforward theorem from revealed preference is not applicable. We speculate on these possibilities later in this section, but retain for now the assumption that *homo economicus* is deciding whether or not to turn on the fans.

The positive externality from installation of radon remediation equipment can be dealt with through a regulatory strategy, through public provision of radon remediation equipment, or by providing monetary incentives for private provision. Public provision of remediation equipment or providing monetary incentives essentially changes the capitalization value of the equipment in our model. Public provision of remediation equipment would correspond to a 100% subsidy with

partial monetary incentives resulting in an increased capitalization percentage. At an action level of 4 pCi/l (the EPA's guideline), public provision of remediation equipment to 6,000,000 eligible housing units at a cost of \$1,200 each would cost approximately \$7.2 billion. It seems unlikely, in the current political climate, that such expenditure would be undertaken publicly. Private monetary incentives would also involve budget costs. Such incentives would also be very ineffective in the short run, given our estimate that over four-fifths of eligible households at any given time would obtain no surplus from having access to a remediation system - that is, they would not even turn on the fans.

Notice that even if the remediation equipment is completely paid for by the government, many households with radon concentrations above 4 pCi/l would not operate the equipment. This can be observed since a complete subsidy is identical (in our model) to all households already having remediation equipment installed (These policy functions are displayed in the top row of Figure 5). Never smokers rarely operate the fans and even many former smokers do not find it worthwhile to operate the fans. Our simulations suggests that the only subpopulation that is likely to operate the fans at the EPA's guideline of 4 pCi/l are middle aged smokers.

5.1 Alternative Scenarios

Up to this point we have only considered models where all households had complete information about the health effects of radon exposure, the capitalization of an investment in remediation equipment, and their probability of moving. We now consider two variants of the models.

The first variant of our model we consider is a situation where investment in remediation equipment is not capitalized into the housing value at all. If our model is incorrect to assume that every one has full information about the health effects of radon (as it likely is), we are also likely to misestimate the capitalization of remediation. If the population systemically underestimates their risk of radon induced lung cancer, our capitalization estimates will be too high. In the limiting case,

where the population either assumes they have no risk of radon induced radon lung cancer or have no knowledge of the risks (and therefore assumes there is none) there will not be any capitalization of remediation equipment. The contour plot of household's policy functions in this scenario are shown in Figure 6.

These policy functions look quite similar to those from the baseline scenario where there is full information about the radon health costs.²² The stalactites are slightly smaller than the baseline scenario but there is little difference. This is a result of the fact that capitalization in the baseline scenario is approximately 10%, so even when fully informed, households are already bearing most of the capital cost of remediation.

The second variant of our model we consider is a situation where our households never move from the house they currently occupy. While this situation is clearly not something that would occur, most cost benefit analyses assume that all of the benefits of remediation equipment accrue to the current homeowner. In this situation, the externality associated with the installation of remediation equipment is internalized because the household will not move and receives all of the benefit of the remediation equipment. In this model we assume that households have moved at the average probabilities before the simulation begins, but then once made aware of the risk of radon, never move again.

The policy functions shown in Figure 7 come from this model.²³ We can see that more households choose to install remediation equipment, particularly among younger cohorts. The substantial increase in installation among younger cohorts is due to the fact that they have a shorter radon exposure history and have the most to gain if they do not move in the future. We also see that, even at high levels of radon a substantial proportion of the population will not install remediation equipment, notably all households that have never smoked.

²²Clearly, only the decision of installing remediation equipment is affected by forcing the capitalization of the investment to be zero. If there are already remediation equipment in the house, the household's decision does not change.

²³Again, this change to the model will not have any effect on household's decisions to operate the fans once they are installed, so the top row of contour plots do not change.

5.2 Information Requirements

To be effective, the "realistic" policy approach discussed in this section requires that householders be well-informed about the radon-related risks that they face and about the effectiveness of radon remediation systems in reducing that risk. A regulation requiring that remediation systems be installed will have no health benefits unless households turn on the fans. Our analysis assumes that households have sufficient information to make that decision.

Making such information generally available will surely require a costly public information campaign. Implicitly, the analysis that we have conducted here supposes that such a campaign would be inexpensive relative to the costs of remediation themselves (a reasonable assumption) and effective (an assumption that may or may not be reasonable). Thus, before pursuing any policy of public provision or subsidization of remediation equipment we would propose extensive test-marketing and experimentation of advertising protocols. The object would be to see what fraction of households, at what costs, would become well-informed about the costs and consequences of operating radon remediation systems. Note that if households systematically believe that such systems are substantially less effective than they are, a policy that promotes general availability of such systems will fail to meet a benefit-cost test. Thus the marketing research that we call for here is a fundamental prerequisite of a successful remediation policy.

Subsequent to such a study, it would be possible to reliably predict who would operate the systems were they available, and thus to reliably evaluate the policy of "remediate on transfer" that looks so promising based on the rational-behavior analysis we have reported here.

6 Conclusions

Because of mobility, remediation of residential radon exposure has all the earmarks of a classic public health problem: the benefit to the community of installing remediation equipment considerably exceeds the benefit derived directly by those members of the community undertaking the

requisite action. Our results suggest that mobility could be a very significant barrier to reducing residential radon exposure because much of the initial investment in remediation equipment is not likely to be capitalized into housing prices. Our simulations suggest that in the case that everyone is well informed about the health risks of radon exposure, approximately 10% of the initial investment will be reflected in the resale price of the house, and only about 0.3% of houses would have remediation equipment installed.

Assuming that households are well-informed about the health risks associated with radon exposure, our simulations suggest that very few households will find it in their best interest to follow the EPA's guideline to install remediation equipment at a concentration of 4 pCi/l or above. However, if the remediation costs are heavily or completely subsidized, an action level between 4 and 6 pCi/l is justified for both current and former smokers, though households who have never smoked are unlikely to find it worthwhile to operate remediation equipment even if capital costs are fully subsidized.

In the absence of a capital subsidy, very few households will find it worthwhile to install and operate remediation equipment. Our simulations suggest that among former smokers only households between the ages of 40 and 60 in houses with a radon concentration above 12 pCi/l will install remediation equipment. The among current smokers, the age range approximately doubles to 30-85 years old and the required radon concentration falls to approximately 8 pCi/l. Most strikingly, households who have never smoked will never find it worthwhile to install radon remediation equipment at any concentration of radon less than 20 pCi/l or age.

Our simulations suggest that there is important dimensions of heterogeneity both across ages and smoking histories to consider when designing a policy toward residential radon. While previous studies have examined the aggregate costs and benefits of a homogeneous policy our results suggest that a targeting of policy at subpopulations, particularly smokers, would increase the benefit cost ratio substantially.

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7 Tables

Table 1: Constants used in the BEIR VI model of radon related lung cancer mortality

γ_1		1.00
γ_2		0.78
γ_3		0.51
$\Psi_{s=0}$	if age < 55	0.1536
$\Psi_{s=0}$	if 56 < age < 65	0.0876
$\Psi_{s=0}$	if 66 < age < 75	0.0446
$\Psi_{s=0}$	if 76 < age	0.0138
$\Psi_{s=1}$	if age < 55	0.06912
$\Psi_{s=1}$	if 56 < age < 65	0.03942
$\Psi_{s=1}$	if 66 < age < 75	0.02007
$\Psi_{s=1}$	if 76 < age	0.00621

Table 2: Percent of Population that Moved Residences by Age

Age	Percent Moved
20-24	35.2
25-29	32.4
30-34	22.0
35-44	14.8
45-54	9.3
55-64	7.0
65-84	4.3
85+	4.7

Source: US Census Bureau

Table 3: Parameters of Economic Model

u	Flow utility from housing
s	Smoking status (current, former, or never smoker)
a	Age (20-110)
r	Radon concentration, before remediation, in current house (0-20)
w	Vector of 25 years of cumulative radon exposure
f	Indicator variable =1 if fans are operated in current period
c	Cost of operating the fans for 1 period; \$125
π	Capitalization of remediation equipment into housing value, endogenously determined
k	Cost of installing remediation equipment; \$1,200
θ	Denotes a “type”; unique combination of (s,a,r,w)
λ_θ	Probability of dying this period for type θ
δ_θ	Probability of moving next period for type θ
β	Discount factor; 0.95
p	Probability that the next house has remediation equipment installed, endogenously determined

Table 4: Capitalization and Prevalence of Remediation Equipment

	Value of a Life Year				
	\$100,000	\$200,000	\$300,000	\$400,000	\$500,000
Capitalization (Percent)	4.0	7.9	9.5	12.3	12.7
Percent of Housing Stock with Remediation	0.000	0.001	0.003	0.004	0.006

Table 5: Peak Age and Radon Levels for Remediation Decisions

	Value of a Life Year				
	\$100,000	\$200,000	\$300,000	\$400,000	\$500,000
Houses with Remediation Equipment Already Installed					
Non-Smokers - Age	—	—	50.1	49.7	49.5
Radon Level	—	—	18.3	14.2	11.8
Former Smokers - Age	49.7	48.8	48.2	47.1	48.9
Radon Level	14.7	8.3	6.2	5.2	4.5
Current Smokers - Age	48.8	45.9	43.8	42.1	43.7
Radon Level	7.5	4.8	4.0	3.6	3.2
Houses without Remediation Equipment Already Installed					
Non-Smokers - Age	—	—	—	—	—
Radon Level	—	—	—	—	—
Former Smokers - Age	—	45.8	47.4	45.6	45.3
Radon Level	—	18.0	12.4	9.6	8.0
Current Smokers - Age	41.8	45.6	46.3	45.3	45.2
Radon Level	14.6	9.0	6.6	5.3	4.8

8 Figures

Figure 1: Decision Tree for Households

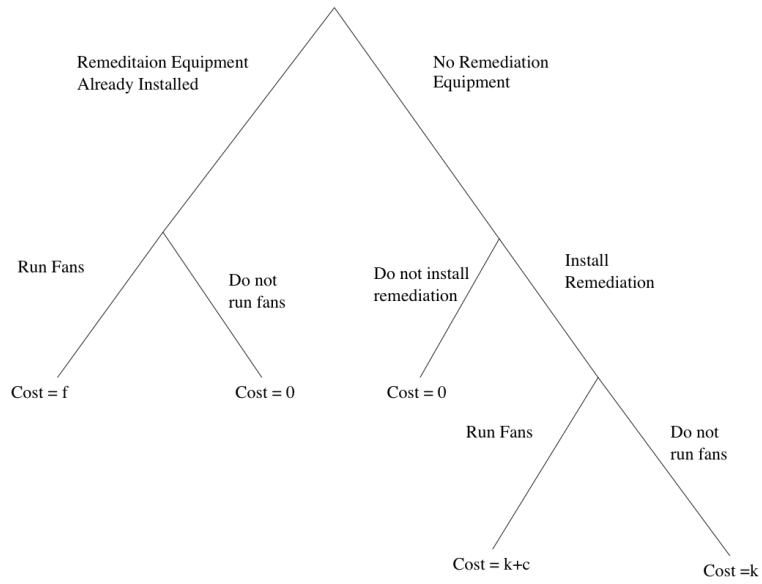


Figure 2: Probability of Dying before reaching the next age

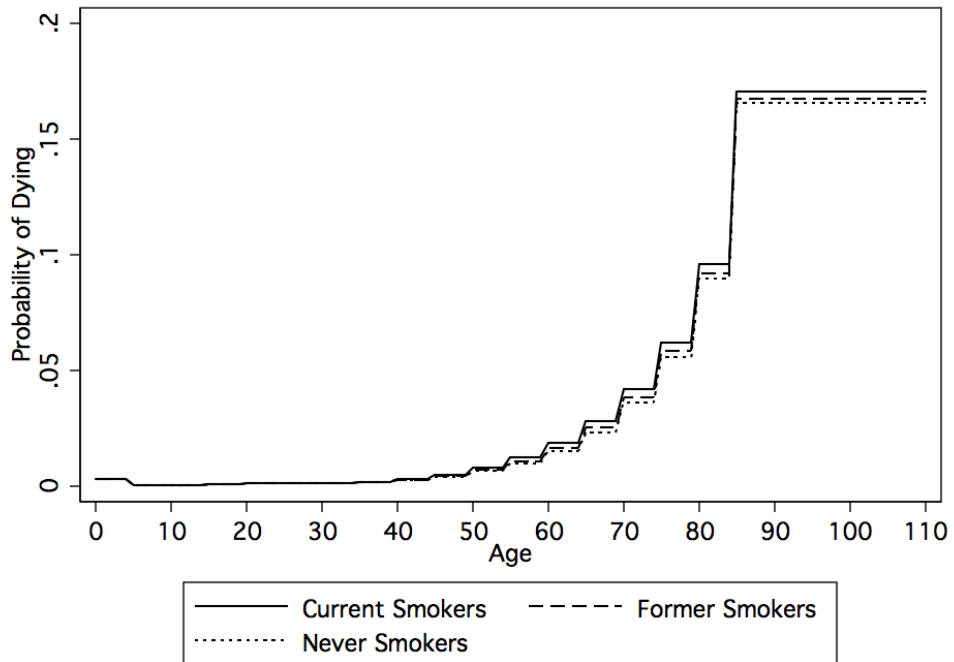


Figure 3: Density of Ages in the United States, 2006-2008

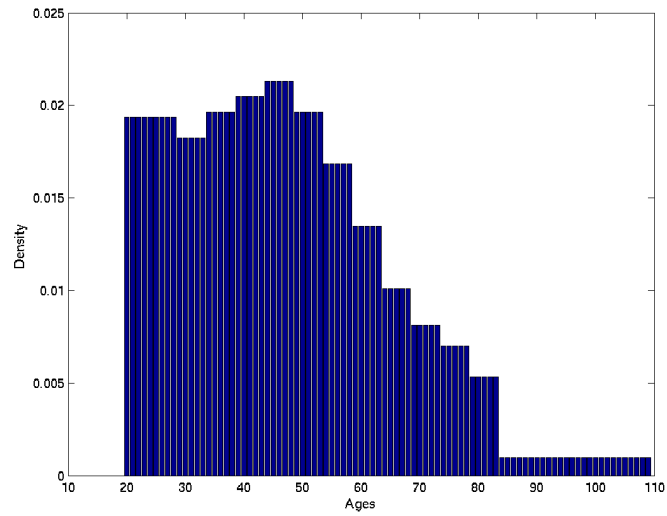


Figure 4: Density of Radon Concentrations in an Unremediated Housing Stock

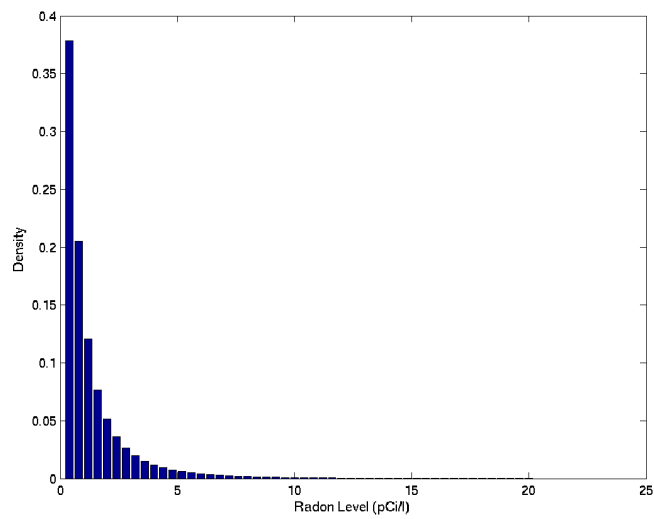


Figure 5: Policy Function for a Typical Household's Remediation Decision with a Life-Year Valuation of \$300,000

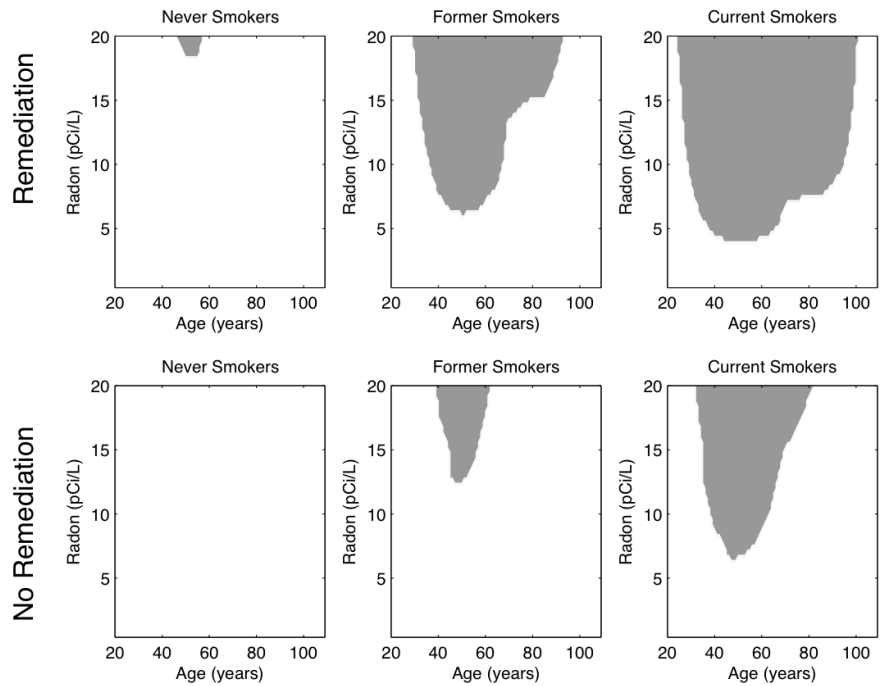


Figure 6: Typical Policy Function for a Household's Remediation Decision with a Life-Year Valuation of \$300,000 if There is No Capitalization of Remediation Equipment

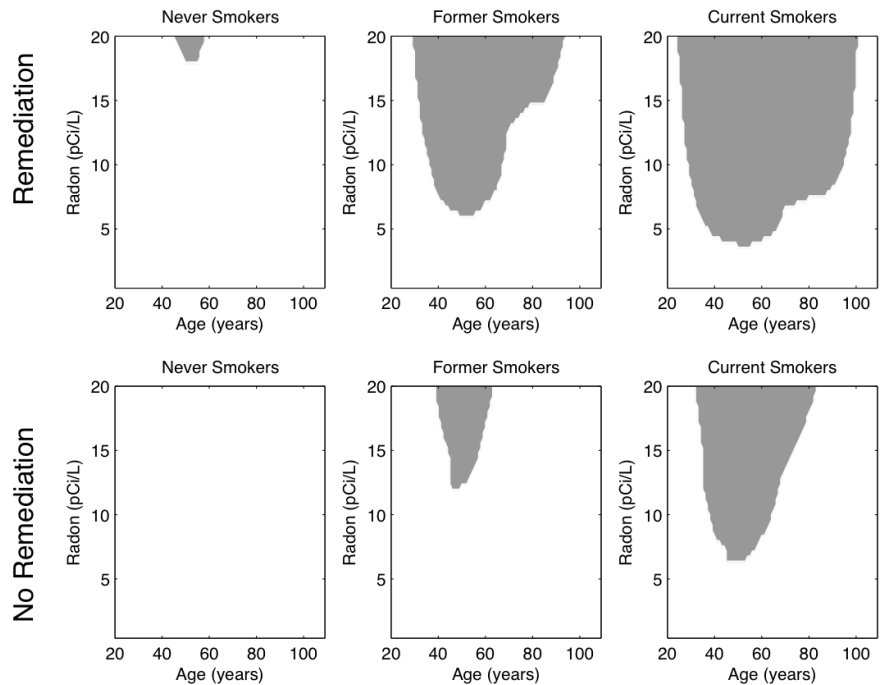


Figure 7: Policy Function for a Household's Remediation Decision with a Life-Year Valuation of \$300,000 if the Household Will Never Move

