COSTS AND BENEFITS OF MITIGATING RADON IN DRINKING WATER

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The Environmental Protection Agency (EPA) is considering regulating radon, a naturally occurring soil gas dissolved in drinking water, because it poses a lung cancer risk. Benefits and costs of compliance are estimated for 29 water systems with radon above the proposed maximum contaminant level. The estimated cancer risk is three times higher than assumed by EPA, making it likely that a national regulatory standard of 300 picocuries per liter of water would pass a cost-benefit test. Site specific estimates of compliance costs are also substantially greater than EPA estimates. Nevertheless, the estimated cost per avoided death is only about $1 million.

Keywords: *radon; cost-benefit analysis; water systems; mitigation; cancer*

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Radon is a naturally occurring radioactive soil gas suspected of increasing the risk of lung cancer when inhaled, a risk second only to smoking as a cause of lung cancer. The gas can enter the home via cracks in basement walls and floors. But radon gas can also be found dissolved in drinking water drawn from underground sources (wells and springs), which is released into the air when faucets and showers are in use. The National Research Council (NRC) estimates that 160 Americans die annually from lung cancer caused by radon in drinking water (NRC, 1999, p. 18). This compares with 18,200 deaths per year attributed to airborne radon (i.e., from basement cracks). Unlike basement radon, waterborne radon may involve sufficient market failure arising from imperfect consumer information and natural monopoly in public water supply to justify government regulation.[1]

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The Safe Drinking Water Act requires the Environmental Protection Agency (EPA) to set standards to reduce the risk from radon in drinking water and to weigh the costs and benefits in doing so. But the language is vague and leaves considerable discretion to regulators. The EPA has been grappling with the radon issue for a decade. Providing a safe, reliable, and economical supply of drinking water is the primary concern of managers of public water supply systems. As one of the principal stakeholder groups, water system management should understand the main issues of the policy debate because they will ultimately be charged with implementing any new policy. For example, what treatment technologies are likely to be most cost-effective in mitigating radon? Moreover, as the list of health and safety regulations grows (e.g., radon and arsenic), the economic viability of the smallest water systems comes into question because the bulk of compliance costs are in the nature of fixed costs, which must be spread over a small customer base.

As is frequently the case with environmental risks, controversy surrounds the scientific evidence. Risk estimates used by the EPA are based solely on linear extrapolation of exposure of uranium miners to levels of radon far in excess of what is found in homes (NRC, 1999, pp. 82-104). The epidemiological evidence is uncertain because of the long lag between exposure and the onset of disease (20 years or more) and the confounding influence of smoking. Nevertheless,

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the Clinton Administration's EPA proposed a complex national program for mitigating radon in drinking water, which is under review by the Bush Administration. The EPA's (1999) cost-benefit analysis found that costs exceeded benefits by a wide margin for every maximum contaminant level considered, even using a generous $5.8 million to value each statistical life saved (pp. 11-12). For example, at the benchmark maximum contaminant level (MCL) of 300 picocuries per liter of water (300 pCi/L), total annual costs are estimated at $407.6 million, whereas benefits are $362 million.[2] To finesse the problem, EPA proposed an alternate MCL of only 4,000 pCi/L for drinking water, combined with a program to reduce basement radon to the extent required to accomplish the same reduction in annual deaths of 62. Under this scenario, the annual benefit-cost ratio varies from 3:1 to 6:1 (p. 113).

Hahn and Burnett (2001) have sharply criticized the EPA's cost-benefit analysis as inadequate and misleading. For example, they charge that EPA assumed a zero cost for reducing risks from basement radon, and that even the much-relaxed water radon standard of 4,000 pCi/L does not pass the benefit-cost test, a fact disguised by combining water and basement radon numbers (p. 10). More important, Hahn and Burnett view the basement radon component of the EPA plan as unrealistic because it assumes that compliance cost is minimized by a system of purchasing credits from other parties.[3] They conclude that "the EPA should not pass new federal regulations that require reductions in exposure to radon in air or water because the agency has not shown that the benefits exceed the costs for such regulations" (p. 14).

This article undertakes a microlevel study of the costs and benefits of a 300 pCi/L MCL of radon in drinking water for 29 small community water systems in New York, a state with a significant exposure problem. The focus is on small systems because they disproportionately draw water from underground sources and mitigation represents a significant cost per customer served. The national EPA benefit and cost estimates are macrolevel in that they rely on generic estimates of compliance costs and risk fitted to the distribution of water systems by size and radon level across the nation. This study employs system-level readings of radon, population at risk, compliance costs, and so forth. Apart from testing the EPA's methods and data, this study is the first to directly estimate the lung cancer risk from radon in water. The basic conclusion is that the risks from radon in drinking water are far greater than hitherto assumed, and that compliance costs in New York are likely to be significantly higher than estimated by EPA. This article finds that regulating radon in drinking water does appear to pass the social cost-benefit test, both in New York and nationwide, with an estimated cost of about $1 million per life saved. Basically, those at risk from lung cancer would be willing to pay more than the cost of mitigating this risk. Furthermore, because of economies of scale in public water supply, the compliance cost per customer tends to decline sharply as water system size increases. Efficient social policy would encourage system consolidation to spread the fixed costs, but this does not appear to be a priority of the EPA or the authorities in New York State.

A variety of factors shape the risk exposure people face: the level of radon dissolved in drinking water, the volume of water used (e.g., time spent showering), the transfer of the radon into the indoor atmosphere, the breathing rate, the rate of radioactive decay, the amount of time people spend indoors, and how long they live in the same house.

EPA Estimates of Deaths Due to Radon in Drinking Water

Inhalation of the radioactive decay products (progeny) of radon gas is the principal source of lung cancer risk (NRC, 1999, p. 265). A variety of factors shape the risk exposure people face: the level of radon dissolved in drinking water, the volume of water used (e.g., time spent showering), the transfer of the radon into the indoor atmosphere, the breathing rate, the rate of radioactive decay, the amount of time people spend indoors, and how long they live in the same house. In addition, the risk per unit of exposure is subject to uncertainty. To account for the uncertainty of these variables, EPA employed Monte Carlo simulation models to estimate the annual number of deaths due to radon (EPA, 1999, Appendix F). The risk estimates are normalized to the risk of cancer death per year per pCi/L of drinking water for the general population, a gender and smoker weighted average. EPA uses an annual death risk of 8.93×10^{-9} per pCi/L of water (EPA, 1999, Table A.1-2).[4] When multiplied by the population served and amount of radon in the water of each community system, one may predict the annual number of lung cancer deaths. This is shown in Table 1 for the 29 community water systems under investigation. (The basis for

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Table 1: Environmental Protection Agency (EPA) Estimated Annual Lung Cancer Deaths

Water System	*Predicted Deaths*
Addison Village	0.01439
Angelica Village	0.00644
Arkville Water District	0.00162
Belmont Village	0.00562
Blooming Grove 1	0.02083
Blooming Grove 3	0.00069
Cohocton Village	0.00487
Croton Falls Village	0.02170
Delhi Village	0.03356
Deposit Village	0.02851
Friendship Town	0.00431
Greenwood Water District	0.00095
Hobart Village	0.00511
Holley Village	0.00922
Hunter Water Corporation	0.01518
Marathon Village	0.00840
Mayville Village	0.00716
Middleburgh Village	0.00773
Millport Village	0.00253
Newark Valley Village	0.00772
Prattsville Water District	0.00221
Red Hook Village	0.00712
Salamanca City	0.05344
Sinclairville Village	0.00373
South Dayton Village	0.00221
Unadilla Village	0.00802
Victor Village	0.01051
Washingtonville Village	0.02053
Wellsburg Village	0.00397
Summed deaths	0.318

selecting these systems is discussed below.) These predicted deaths are due to the combined risk from inhalation of radon gas and its radioactive progeny, as well as the risk from ingestion (88% of risk stems from the progeny, however). The summed annual deaths of 0.318 in Table 1 imply that approximately 1 extra death every 3 years is attributable to radon in drinking water.

EPA Compliance Cost Estimates for Radon Mitigation

Aeration, filtration, and storage (to allow natural dissipation) are the basic treatment techniques available to mitigate radon in drinking water, with the least-cost technology largely dependent on the daily water flow (EPA, 1999, Appendix B). EPA has estimated regression equations for each candidate technology, with capital, operating, and maintenance costs a function of daily water production.[5] The water production of each of the 29 systems under review were plugged into the regression equations for each technology to determine the least cost of compliance for each water system.[6,7] One interesting aspect of radon removal is that the mitigation cost is relatively insensitive to the percentage of radon removed (EPA, 1999, p. 11). For example, annual costs for removing 99% of radon in the village of Belmont are $8,824 versus $8,484 for 80% removal, an incremental cost of just 4%.

Table 2 presents the annual EPA-based compliance cost for each water system. Twenty-two systems should employ Diffused Bubble Aeration (DB) to remove radon at least cost, 4 systems should employ a technology known as Granular Activated Carbon (GAC), and 3 should use storage. DB involves injecting air bubbles into the water to cause the dissolved radon gas to dissipate into the atmosphere. With the GAC method, the surface of activated carbon (charcoal) attracts and accumulates the radon as the water passes through the filtration system. Both tech-

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Table 2: Environmental Protection Agency (EPA) Estimated Annual Compliance Costs for Radon Removal (includes capital, operating and maintenance cost, and 99% removal)

Water System	*Annual Cost ($)*	*Radon (pCi/L)*	*Population Served*
Addison Village	9,383	875	1,842
Angelica Village	7,150	760	950
Arkville Water District	5,111	725	250
Belmont Village	8,824	475	1,325
Blooming Grove 1	10,965	1,555	1,500
Blooming Grove 3	7,257	370	208
Cohocton Village	5,519	635	859
Croton Falls Water District	1,324	11,250	216
Delhi Village	20,574	1,115	3,374
Deposit Village	14,074	1,535	2,080
Friendship Town	6,885	350	1,380
Greenwood Water District	725	410	260
Hobart Village	5,230	1,505	380
Holley Village	8,087	480	2,150
Hunter Water Corporation	11,023	1,545	1,100
Marathon Village	7,728	850	1,107
Mayville Village	21,439	490	1,636
Middleburgh Village	14,563	625	1,385
Millport Village	1,324	645	440
Newark Valley Village	11,753	690	1,253
Prattsville Water District	2,496	660	375
Red Hook Village	9,353	360	2,214
Salamanca City	43,426	855	7,000
Sinclairville Village	14,354	590	708
South Dayton Village	5,980	375	661
Unadilla Village	5,720	710	1,265
Victor Village	11,753	510	2,308
Washingtonville Village	68,775	460	5,000
Wellsburg Village	10,585	685	650
Mean	12,000		

NOTE: Least cost mitigation is by Diffused Bubble Aeration, except for Granular Activated Carbon in Millport, Prattsville, Greenwood, and Croton Falls; and storage is least cost in Sinclairville, Mayville, and Wellsburg because they currently do not chlorinate. Washingtonville must add chlorination (included in its cost) because it is too large to utilize storage. Treatment costs refer to single site (e.g., well) mitigation, except in Salamanca where two wells were tested and found to have elevated levels of radon.

nologies involve a central water treatment plant. Because aeration or filtration may introduce infectious materials into the water supply, EPA adds the cost of chlorination for those systems not already disinfecting. Four of the 29 water systems presently do not disinfect with chlorine. Three of these systems are best off using storage instead of treatment, but 1 system (Washingtonville) must incur an extra $50,000 annual compliance cost to chlorinate.[8] In developing national estimates of radon compliance costs, the EPA added the cost of chlorination for those systems not currently disinfecting—as many as 50% of the smallest systems and one third of the largest (EPA, 1999, p. 74). In other words, radon mitigation includes the cost of chlorination but no additional health benefits are added. Because chlorination is so widely viewed as a safe and cost-effective treatment of drinking water, it may be reasonable to assume the benefits and costs of chlorination offset each other. Thus, EPA may have overstated the costs of radon compliance.[9] The EPA also assumed that each water source site (e.g., well or spring) would require mitigation. Because even small systems frequently draw water from more than one well, not all of which exhibit elevated levels of radon, this tends to inflate cost estimates. The cost estimates in Table 2 assume that only the number of source sites actually tested and exceeding 300 pCi/L are subject to mitigation. This difference is significant because all costs would be multiplied by a factor of 2, 3, or even 6 if all wells were automatically treated. In addition, EPA does not consider the possibility of shutting down radon-heavy wells and increasing output from clean wells (EPA, 1999, p. 68).

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As is frequently the case with proposed environmental regulations, industry estimates of compliance costs differ significantly from those of the EPA. Raucher and Drago (1992) developed cost estimates based on engineering cost functions, that is, an engineering design for each treatment technology and water flow rate is put together and costed out. Overall, Raucher and Drago estimate annual compliance costs for a 300 pCi/L MCL of $2.5 billion (in 1990 dollars), far in excess of the $407.6 million EPA estimate (in 1997 dollars), with most of the difference due to the treatment cost. For example, the capital cost estimated by Raucher and Drago for packed tower aeration for the three smallest size water systems is $130,000, $180,000, and $250,000, respectively (Raucher & Drago, 1992, Table 7).[10] This involves 99% radon removal with no chlorination. EPA's estimate of the capital cost for the same technology, radon removal rate, and system size is $30,486, $43,085, and $58,403, respectively (EPA, 1999, Appendix B-4). Raucher and Drago also estimate annual operating costs of $16,000, $18,000, and $21,000, compared to $2,292, $4,110, and $8,113 estimates by the EPA (1999, Appendix B-8). These large discrepancies exist across the various technologies and system sizes considered, which make clear the need for more realistic estimates based on actual water system cost data.

It should be noted that compliance cost is not identical with social opportunity cost, the latter being the relevant concept in cost-benefit analysis. For example, to the extent radon mitigation causes water systems to raise their prices, their customers will suffer a loss of consumer surplus. And if treatment to mitigate radon results in premature retirement of specialized water plant capital, this also counts as a social cost. Thus, compliance cost, either those of the EPA or those estimated in this article, should be viewed as a lower bound estimate of social opportunity cost.

Costs and Benefits Based on EPA Estimates

Reducing radon risks in drinking water is socially efficient if the water users are willing to pay more to reduce the risk than it costs to do so.

Reducing radon risks in drinking water is socially efficient if the water users are willing to pay more to reduce the risk than it costs to do so. Thus, the gainers from radon regulation could compensate the losers and still be better off. This is referred to as the Potential Pareto Improvement criteria. Absent actual compensation, one can never be certain if gains enjoyed actually outweigh the losses incurred in a welfare sense.

A central element in assessing the benefit of reducing the lung cancer risk resulting from reducing radon in drinking water is the aggregate willingness to pay of those enjoying the lower risk. The idea of assigning a dollar value to human life is offensive to some people. This prejudice is reinforced by the widespread practice in the legal system of awarding damages to the survivors of an accident equal to the discounted value of the decedent's expected future lifetime earnings. Under this approach, a poor person, a female, or an older person's life is worth less than a prime age, well-educated male. But much of the distaste arises from a misconception of the Value of Life (VSL) that is employed in cost-benefit analysis. In cost-benefit analysis, the appropriate value is the aggregate willingness to pay for the risk reduction normalized to each death avoided. In particular, VSL is not a sum that known victims would accept to voluntarily die. VSL refers to anonymous deaths (i.e., the identity of victims is unknown ex-ante), hence the term *statistical death*. Suppose a group of 10,000 workers is subject to a 1 in 10,000 risk of dying each year. If each worker would be willing to pay $500 per year to reduce to zero the probability of one of their number dying each year, then the aggregate willingness to pay is $5 million per life saved. This is the correct value of a statistical life, which is to be compared with the cost of reducing the risk (e.g., safety equipment, worker training, or radon mitigation). A key aspect of cost-benefit analysis is assigning a credible and defensible value to a statistical life since it makes operational the Potential Pareto Criterion.

There is a considerable literature about the theory and estimation of VSL, summarized by Boardman, Greenberg, Vining, and Weimer (2001, pp. 392-395). Some estimates are based on labor market risk premiums, whereas others are derived from revealed preferences about purchases of auto safety devices and smoke detectors. The range of credible estimates of VSL (in 1999 dollars) is between $2.5 million and $4 million. But the EPA prefers a VSL of $5.8 million based on its own survey of the literature (p. 63). Although the Office of Management and Budget

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Table 3: Threshold Values of a Statistical Life Based on Environmental Protection Agency (EPA) Risk and Cost Estimates (rounded, in dollars)

Water System	*Break-Even Required Value of Life (VSL)*
Addison Village	652,000
Angelica Village	1,109,000
Arkville Water District	3,158,000
Belmont Village	1,570,000
Blooming Grove 1	526,000
Blooming Grove 3	10,559,000
Cohocton Village	1,133,000
Croton Falls Water District	61,000
Delhi Village	612,000
Deposit Village	494,000
Friendship Town	1,596,000
Greenwood Water District	762,000
Hobart Village	1,024,000
Holley Village	878,000
Hunter Water Corporation	726,000
Marathon Village	920,000
Mayville Village	2,995,000
Middleburgh Village	1,884,000
Millport Village	522,000
Newark Valley Village	1,522,000
Prattsville Water District	1,129,000
Red Hook Village	1,314,000
Salamanca City	812,000
Sinclairville Village	3,848,000
South Dayton Village	2,702,000
Unadilla Village	713,000
Victor Village	1,118,000
Washingtonville Village	3,349,000
Wellsburg Village	2,662,000
Mean	1,736,000

issues fairly detailed guidelines for cost-benefit analysis, no administration has ventured to offer a benchmark VSL. As noted by Kopp, Krupnick, and Toman (1997), "Estimates of the value of a statistical life taken from summary reviews and specific studies are widely used and multiplied by expected deaths *delayed* to obtain mortality benefits from a particular program" (p. 19). Note the emphasis on delayed deaths, because lives cannot literally be saved but instead prolonged. Although VSL estimates based on revealed preferences, such as higher wages for riskier jobs, are generally thought more reliable than interview-based contingent valuation estimates, it is unclear if labor market death risks fully transfer to the type of environmental hazards under consideration here. Workers may be younger and less risk averse than the general population, for example. However, the entire population of a water supply system should be viewed as willing to pay because all who consume water are exposed to risk, even if the onset of disease is decades hence. Hahn and Burnett (2001) adjust the EPA's $5.8 million VSL down to $2.4 million to allow for this latency, that is, willingness to pay to avoid future risk is worth less today.[11] Some authors have argued that the VSL should be adjusted for the type of risk (e.g., voluntary or not, dread of cancer), but the EPA's Science Advisory Board has recently concluded that the evidence presently available justifies adjustment only for timing (cited in Hahn & Burnett, 2001, p. 9). The approach taken here is to determine a threshold or break-even value of a statistical life for each water system by dividing the annualized compliance cost estimates by the annual reduction in cancer risk, in addition to the aggregated cost of saving a statistical life approach used by EPA.[12] These break-even values can then be compared with the benchmark values of VSL cited above. These threshold values are shown in Table 3, based on Tables 1 and 2.

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Just one of the water systems in Table 3 requires a value of statistical life higher than the $4 million upper bound of the consensus range of $2.5 million to $4.0 million, and just seven require a VSL above $2 million. Only one water system requires a VSL in excess of the EPA's own preferred value of $5.8 million. Furthermore, the aggregate cost per life saved is only about $1 million ($350,000/0.318). The outlier VSL is Blooming Grove 3, which serves only 208 people and has a radon level of just 370 pCi/L. It thus appears that direct mitigation of radon in drinking water is highly cost-effective for this particular set of systems, even using the EPA's own template for assessing costs and benefits. However, as the balance of the article demonstrates, this template appears to suffer from some serious shortcomings.

New Compliance Cost Estimates

The EPA compliance cost estimates . . . do not allow for regional differences in costs. . . . In addition, the EPA did not consider new ground water sources as an option.

The EPA compliance cost estimates presented above do not allow for regional differences in costs. New York is a high-cost location, and site-specific estimates are likely to be more accurate. In addition, the EPA did not consider new groundwater sources as an option. The State Department of Health Cancer Registry reports lung cancer deaths by zip code. The New York State Environmental Facilities Corporation and the Health Department jointly administer a revolving loan fund for community water supply investments, which is used to estimate new compliance costs. In addition, the Health Department tested 429 water systems for radon in 1989-1990 (New York State Department of Health [NYSDOH], 1990). Twenty-nine community water systems in New York were selected for study based on several criteria: radon levels in excess of 300 pCi/L, having recently undertaken or proposed an upgrade of their water supply system, and serving a catchment area compatible with the lung cancer zip code data. The mean population served of the 29 water systems is 1,512 persons, ranging from 208 to 7,000. The mean radon is 1106 pCi/L, ranging from 350 to 11,250.

The Drinking Water State Revolving Fund (DWSRF) subsidizes drinking water infrastructure projects with grants and low-interest loans. Thirty-four community water systems appear in the radon testing and DWSRF databases, including the 29 listed above in Tables 1, 2, and 3; the other 5 could not be included because complete information was not available (most of the excluded systems are mobile home parks). However, all 34 have recently proposed or actually undertaken infrastructure investments that are comparable to radon mitigation (e.g., a new well, treatment plant, or storage facility). The DWSRF project cost data is used to estimate regression equations for new groundwater sources, storage facilities, and treatment plants.[13] The estimated capital costs are converted to annual amounts using the same 7% discount rate and 20-year capital life assumed by EPA. New wells are the cheapest alternative by far for mitigating radon. Annualized costs for a new well are about $33,500, as compared to $90,000 for treatment or storage. It is assumed that operating costs (e.g., pumping) of a new well are the same as for existing wells. These cost estimates are significantly greater than those put forward by EPA (compare Tables 2 and 4). Table 4 also presents the revised break-even VSLs based on these new costs and the EPA risk estimates from Table 1.

With a mean break-even VSL of $7.39 million, the cost-effectiveness of radon mitigation in New York appears much less attractive when based on actual compliance costs and EPA risk estimates. This result occurs because compliance costs are almost three times larger than estimated using EPA methods. Nevertheless, the aggregate cost per life saved of $3 million falls within the range of consensus estimates.

The outlier VSLs in Table 4 are small systems: Blooming Grove 3 (208 people), Arkville (250 people), Greenwood (260 people), Prattsville (375 people), Millport (440 people), and South Dayton (661 people). Water system consolidation offers an alternative to make mitigation more economically attractive, spreading the treatment cost over a larger service population. But historically it has proven difficult to persuade local governments to consolidate any activity (e.g., public safety, roads) and thus surrender perceived local autonomy.

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Table 4: New Annual Cost of Compliance and Break-Even Value of Life (VSL) Using Environmental Protection Agency (EPA) Risk (rounded, in dollars)

Water System	*Compliance Cost*	*Break-Even Value of Life (VSL)*
Addison Village	32,588	2,264,000
Angelica Village	29,574	4,587,000
Arkville Water District	26,362	16,287,000
Belmont Village	31,906	5,677,000
Blooming Grove 1	34,526	1,658,000
Blooming Grove 3	30,004	43,658,000
Cohocton Village	26,954	5,534,000
Croton Falls Water District	25,447	1,173,000
Delhi Village	46,762	1,392,000
Deposit Village	38,365	1,346,000
Friendship Town	29,394	6,815,000
Greenwood Water District	25,160	26,430,000
Hobart Village	26,524	5,194,000
Holley Village	31,009	3,365,000
Hunter Water Corporation	34,597	2,280,000
Marathon Village	29,968	3,566,000
Mayville Village	32,767	4,577,000
Middleburg Village	38,975	5,042,000
Millport Village	25,447	10,041,000
Newark Valley Village	35,494	4,597,000
Prattsville Water District	25,806	11,676,000
Red Hook Village	32,552	4,573,000
Salamanca City	91,113	1,705,000
Sinclairville Village	29,394	7,880,000
South Dayton Village	27,959	12,631,000
Unadilla Village	28,605	3,566,000
Victor Village	35,494	3,377,000
Washingtonville Village	43,245	2,106,000
Wellsburg Village	27,815	6,996,000
Mean	33,579	7,390,000

A New Estimate of the Risk of Radon in Drinking Water

Using the actual incidence of lung cancer by zip code, estimates of the number of excess lung cancer deaths during the 1993-1997 period due to radon in drinking water for each community water system are compiled. A significantly positive relationship is detected with an interaction with smoking. In all but a few water systems, the new risk estimates appear to readily justify remediation on economic grounds. More significant, the cost per annual death avoided (or delayed) is only $1 million. Hahn and Burnett (2001) would likely accept that as socially efficient.

Estimating the radon-cancer link poses various difficulties arising from the confounding effect of smoking, the limitations of the available data about exposure to radon, and the lag between exposure and the onset of disease (Stidley & Samet, 1993). It is well-established that the incidence of lung cancer is heavily influenced by age and smoking activity. Housing mobility, errors in measuring indoor and water radon, and tighter modern construction that results in less exchange of indoor air are further examples of potential confounding influences. Fortunately, the use of grouped data in the estimation of the risk from radon in water differs in an important way from previous risk estimates for basement radon. In the case of water, the entire population connected to the water system is at risk, and the measured radon level in the water is a good proxy for exposure. In the case of basement radon, the occurrence by residence is very erratic so that group-level radon readings (e.g., by town or zip code) are less reliable indicators of exposure.

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Table 5: Summary Statistics of Cancer Deaths Regression Analysis Data ($N = 29$)

	Mean	*Range*
Male deaths	8.75	1 to 27
Female deaths	6.37	0 to 19
Water radon (pCi/L)	1,106	350 to 11,250
Basement radon (pCi/L)	9.07	1.8 to 25.4
Median income ($)	28,798	18,885 to 62,323
Smokers	1,570	47 to 3,352

The State Health Department reports total lung cancer deaths during the 1993-1997 period separately for men and women by zip code on its Web site.[14] The combined total by zip code is the dependent variable in the regression equation.[15] The level of radon in drinking water is that shown in Table 2, from the 1989-1990 Health Department survey of water systems.

To allow for smoking activity, the number of men and women in 1990 in each zip code is multiplied by the national proportion of men and women who smoked in 1974.[16] This is a rough adjustment for the level and duration of smoking activity.[17] The smoker variable also controls for population because it is the number of males or females multiplied by a constant (the 1974 rate of smoking).[18] Indoor airborne radon is measured using radon readings gathered by the Health Department from voluntary testing by households, with the mean basement reading for the entire town in that zip code serving as the variable. Incidentally, the occurrence of the two types of radon are slightly negatively correlated with each other (–0.11).[19] The interactive effects of radon and smoking are introduced into the regression model by means of an interaction term: The number of smokers in each community is multiplied by the level of water and basement radon, respectively. Thus, the effect of radon on lung cancer deaths depends on the amount of smoking activity.[20] Finally, median household income is included as a portmanteau variable meant to capture a variety of socioeconomic factors known to influence health status: education, type of employment (e.g., manual vs. white collar), housing mobility, housing quality, access to health care, and so forth. Table 5 presents descriptive statistics of the data. I also developed an estimate of the proportion of the population in each community that resided in the same house more than 19 years (see Anily, Hornik, & Israeli, 1999) to try and capture exposure duration effects. This variable was never significant, perhaps due to the small amount of variation observed, and was therefore dropped.

Considerable controversy about the reliability of so-called ecologic radon studies (i.e., based on group data rather than randomized individual data) was prompted by Cohen (1989, 1995), who found a significant negative relationship between county-level lung cancer rates and levels of indoor (basement) radon gas, a result replicated here. His 1995 study encompasses 1,601 U.S. counties, 300,000 radon measurements, controls for smoking, and 58 socioeconomic variables. According to the NRC (1999), "This finding [of a negative relationship] contradicts the existing risk estimates at low exposure, and a sound reason for the significant negative trend should be sought" (p. 101). In the present situation, basement radon levels and smoking activity are negatively correlated for men and women to about the same degree (about –0.25), and that may account for the statistical results. Stidley and Samet (1993) point to the usual suspects in discussing Cohen's work: measurement error, model misspecification, and failure to adequately control for confounding effects such as the number of cigarettes smoked and duration of smoking. Most of this is familiar territory to economists, who are used to working with "bad" data, that is, not generated from a random experimental design.[21]

Regression Results

Turning to the results for lung cancer deaths in Table 6, the water radon–smoking variable is significantly positive at the 98% confidence level.[22] The strong and significant independent effect of smoking on lung cancer is not surprising. The significantly negative effect of income is

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Table 6: 1993-1997 Estimated Deaths Due to Lung Cancer (*t* ratios in parentheses)

Constant	21.32 (6.99)
Number of smokers	0.01236 (8.95)
Water Radon × Smokers	0.000000309 (2.41)
Basement Radon × Smokers	–0.000292 (2.66)
Income	–0.000784 (5.91)
Adjusted R^2	0.76
Number of observations	29
Breusch-Pagan χ^2 ($df = 4$)	1.41 (critical value 9.49 at 95%)

Table 7: Estimated Lung Cancer Deaths Due to Radon in Water and Break-Even Value of Life (VSL)

Water System	*Annual Deaths*	*Break-Even VSL (rounded, $)*
Addison Village	0.03744	866,000
Angelica Village	0.01674	1,843,000
Arkville Water District	0.00421	6,230,000
Belmont Village	0.01464	2,168,000
Blooming Grove 1	0.05419	634,000
Blooming Grove 3	0.00178	16,696,000
Cohocton Village	0.01268	2,114,000
Croton Falls Water District	0.32507	78,000
Delhi Village	0.08778	530,000
Deposit Village	0.07419	514,000
Friendship Town	0.01119	2,614,000
Greenwood Water District	0.00248	10,080,000
Hobart Village	0.01332	1,982,000
Holley Village	0.02399	1,286,000
Hunter Water Corp.	0.01466	2,348,000
Marathon Village	0.02182	1,366,000
Mayville Village	0.01860	1,753,000
Middleburgh Village	0.02004	1,933,000
Millport Village	0.00657	3,854,000
Newark Valley	0.00347	10,168,000
Prattsville Water District	0.01552	1,654,000
Red Hook Village	0.01848	1,752,000
Salamanca City	0.13830	655,000
Sinclairsville Village	0.00963	3,036,000
South Dayton Village	0.00574	4,843,000
Unadilla Village	0.02083	1,580,000
Victor Village	0.02732	1,292,000
Washingtonville Village	0.05344	805,000
Wellsburg Village	0.01075	2,574,000
Sum	1.06	
Mean		3,000,000

also expected because of occupational, educational, and lifestyle differences associated with income. The significant intercept suggests a base amount of lung cancer, perhaps as a function of aging and genetics. As long as there are no important omitted variables that correlate with the included variables, the estimated coefficients should be unbiased.

Table 7 shows the predicted number of excess deaths per year due to water radon and the break-even value of a statistical life, which also incorporates the new compliance costs estimates. The mean break-even value of a statistical life is a relatively modest $3 million, and the implied cost per life saved is less than $1 million.[23]

This implies that the national cost of delaying a death by mitigating radon in water is substantially less than estimated by EPA.

From a national perspective, the main result in Table 7 is the 1.06 estimated number of lives saved per year due to mitigation, which is more than three times greater than the 0.318 lives saved based on the EPA's risk model applied to these same communities (see Table 1). This implies that the national cost of delaying a death by mitigating radon in water is substantially

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less than estimated by EPA.[24] Seven water systems serve 500 or fewer people, and the cost per life saved is about $4.1 million. Twenty systems serve between 501 and 3,300 people, and the cost per life saved is a mere $782,000. By comparison, the EPA (1999) estimates the cost per life saved for systems with fewer than 500 people at $38.5 million, and at $8 million for systems serving 501 to 3,300 people (p. 133).

The NYSDOH (1990, p. 2) estimates that about 2,000 community water supply wells in New York would require mitigation if the maximum contaminant level for radon in drinking water was set at 500 pCi/L. This implies that approximately 2,700 wells (about 1,400 water systems) require mitigation if the standard were set at 300 pCi/L.[25]

Conclusion

This study estimates the lung cancer risk from radon in drinking water directly instead of relying on extrapolation from the mortality experience of uranium miners. The costs and benefits of mitigating radon in a nonrandom sample of 29 water systems in New York indicate that risk reduction benefits and compliance costs are significantly greater than estimated by the EPA. Lung cancer risk is more than three times greater than estimated using the EPA's own risk assessment model, which indicates that the EPA's nationwide cost-benefit analysis of radon in water significantly overstates the cost per statistical life saved.

Half of the groundwater systems tested by the state health department exceed the benchmark maximum contaminant level of 300 pCi/L. Given the estimated cost per life saved of less than $1 million, authorities in New York should seriously consider regulation of radon in drinking water regardless of the actions of the federal EPA. The author's experience in preparing this article is that local water system managers are unlikely to test or mitigate radon unless required or carried out by federal or state authorities. EPA regulations require water systems to report to their customers each year about the quality of the water supplied, but they only report the results of testing for regulated contaminants. All the radon readings used in this article are the result of a one-time State Health Department testing program in 1989-1990. Perhaps there is a fear of potential litigation if unregulated contaminants are detected. It might make sense to require testing and reporting for radon, with legal immunity, and then allow the local community to decide the merits of mitigation. After all, if benefits indeed exceed costs, the customers of a high-radon system should be willing to pay for the cost of mitigation. This would lessen the need for blanket federal regulations requiring mitigation across the entire nation.

Finally, the EPA and state health departments could consider more actively promoting water system consolidation to minimize the costs of compliance. Annual compliance cost for Arkville (population 250) is $26,362 versus $35,494 for Newark Valley (population 1,253), for example. Existing policy appears to assume that the existing size distribution of water systems is fixed.

Notes

1. Households subject to basement radon assume a voluntary risk because mitigation is cost-effective at the household level (e.g., sealing cracks, ventilation systems, etc.).

2. A picocurie (pCi) is a measure of radioactivity, which is the source of the lung cancer risk. One picocurie represents 2.2 decays per minute. The Environmental Protection Agency (EPA) benefits include 62 avoided deaths per year valued at $5.8 million each, plus 3.6 nonfatal cancers valued at $536,000 each. The nub of EPA's regulatory dilemma is the enormous cost per life saved for small water systems. For water systems serving 500 or fewer customers, national annual compliance costs for a 300 pCi/L standard are $135 million, which saves 3.5 lives per year or $38.5 million per life saved. For water systems serving more than 10,000 persons, compliance costs are $126 million to save 39 lives, or $3.2 million per life saved (EPA, 1999, p. 133). Of 43,900 groundwater systems in the U.S., 29,300 serve 500 or fewer consumers (EPA, 1999, p. 7).

3. As a local monopoly, water systems may have little incentive to mitigate at least cost, even if there are enough local households with elevated basement radon to make compliance with the 300 pCi/L feasible. The EPA assumed water systems will engage in buying and selling of basement and water radon reduction credits when compliance cannot be achieved within the existing service population. Apart from transaction costs, there exist formidable political obsta-

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cles to allowing local residents to continue to be exposed while residents elsewhere enjoy lower risks paid for by their own water supplier. Clearly, Hahn and Burnett (2001) believe that most water systems will feel compelled to directly treat their own water to achieve the 300 pCi/L standard, which implies the $407.6 national compliance cost previously referred to.

4. The EPA (1999) also presents a lifetime unit risk of 6.7×10^{-7} per pCi/L. Because the risk estimates developed later in the article are annual risks, the EPA's own annualized risk was used as the basis of comparison. Although all of the EPA's benefit and cost estimates are annual amounts, they appear to be based on lifetime risk parameters.

5. The EPA analysis does not provide any of the usual regression statistics, such as standard errors, R^2, or sample size. There was no response from EPA to the author's e-mail request for this information.

6. An Excel spreadsheet model was created using the coefficients from the EPA's regression cost equations for radon treatment or disinfecting technologies, all of which are functions of average daily water flow only. Separate equations were estimated by EPA for the various technologies, different system size categories, and capital and operating costs. Functional form is either linear, quadratic, or log-linear, presumably based on goodness-of-fit. The daily water production of each of the 29 systems is inserted into the spreadsheet and the lowest annualized cost of compliance selected. Following EPA practice, daily production is twice the annual average daily flow, presumably to allow for peaking and growth.

7. EPA converts capital costs into annual sums using the official Office of Management and Budget real discount rate of 7% and a 20-year capital life. Alternate discount rates of 3% and 10% are also considered by EPA. Seven percent is an estimate of the average real return on private investment, including risk. Some analysts prefer the method of shadow pricing capital, converting displaced private investment (and consumption) into consumption units and discounting at a social rate of time preference. This approach is rarely used in practice, however, partly because of its sensitivity to alternate values of key parameters and partly because of its opaqueness to noneconomists. Because the present article breaks no new ground in this area, it seems reasonable to mirror the EPA's practice to focus on the differences in compliance costs and risk.

8. Washingtonville's rate of water production is too large to use the storage alternative.

9. The issue is illustrated by noting that the average annual cost of chlorinating the 29 systems is about $32,000, based on EPA cost curves (1999, Appendix F), compared to an annual radon treatment cost of $8,800 using Diffused Bubble Aeration or Granular Activated Carbon. It is the need to chlorinate that requires three water systems to use the more costly option of storage.

10. Very small systems serve 25 to 100 people and have maximum design flow of 0.024 millions of gallons per day (MGD), very small systems serve 101 to 500 people with 0.087 MGD design flow, and small systems serve 501 to 3,300 with 0.27 MGD design flow. These three size categories encompass all but 2 of the 29 systems under investigation. The design flow rates are those used by Raucher and Drago (1992).

11. Hahn and Burnett (2001, p. 9) assume a 7% discount rate, 1% real income growth and income elasticity of demand for risk reduction, and a 15-year period of latency.

12. Consider the example of Addison Village. Its annualized compliance cost is $9,383 (see Table 2), and the estimated annual risk reduction is 0.01439 (see Table 1). If the Value of a Statistical Life (VSL) of $4 million is used, benefits are $0.01439 \times \$4$ million = $57,560, which clearly exceeds the cost. Alternately, we can ask what the value of VSL must be to just make benefits equal costs: $0.01439 \times \text{VSL} = \$9{,}383$, VSL = $652,000. This is what is displayed in Table 3.

13. For new or upgraded groundwater sources, the equation estimated is (t ratios in parentheses)

$$\underset{}{\text{Cost} = 261{,}891 + 0.38\ (\text{Average Daily Production}); R^2 = 0.40, N = 16.}$$
$$\underset{(5.10)\quad(11.61)}{}$$

For storage and treatment, the equation estimated is

$$\underset{(3.56)\quad(1.60)\quad\quad(2.42)\quad\quad(2.40)}{\text{Cost} = 297{,}244 + 339{,}469\ (\text{Stor}) + 833{,}304\ (\text{Treat}) + 345{,}904\ (\text{Dist}) +}$$
$$\underset{(3.45)}{0.50\ (\text{Average Daily Production}); R^2 = 0.33, N = 34.}$$

Indicator variables are used to specify project characteristics. Because the storage coefficient is not significant, the mean cost ($880,964) for nine storage-only projects is used to estimate the cost of compliance with that technology. Even using the insignificant coefficient, storage would be more expensive than the new groundwater option.

14. The Web site is www.health.state.ny.us/nysdoh/cancer.

15. Unlike other studies that use cancer incidence rates (frequently age adjusted), the dependent variable here is the absolute number of lung cancer deaths because of the small number of deaths. No significant results could be obtained using the death rate as the dependent variable, most likely because it introduces the dimensioning variable (i.e., population) into both sides of the equation, which can cause bias of unknown direction (Hough, 1985). An earlier version of this article estimated separate regressions for men and women. The R^2 for those was lower than the combined version, and the water radon coefficient in the female equation was not significant. Combining the lung cancer deaths allows for the effect of secondhand smoke on nonsmoking wives because the right-hand side smoking variable is the total of male and female smokers.

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16. The number of men or women older than age 44 in 1990 estimated to have been smokers in 1974 has a .92 correlation coefficient with the total number of male or female smokers estimated to have smoked in 1974, which is included in the regression analysis, thus effectively capturing the age factor.

17. The 1990 smoking rate for men aged 18 and older is 28.4% versus 43.1% in 1974. For women, the rates are 22.8% versus 32.1%. Using the higher rate allows for the fact that prior smoking activity affects the current incidence of lung cancer.

18. The correlation coefficient between population and smokers is .99.

19. This is policy relevant because it illustrates the difficulty in implementing the preferred EPA strategy of reducing basement radon to offset the water radon risk.

20. Because the long-term trend of smoking is downward, the per capita rate of lung cancer due to radon will likely decline over time. Only fatal cancers are considered because of lack of data, but the EPA estimated only 3.6 avoided nonfatal cases per year versus 62 fatal cases avoided in its analysis of the 300 pCi/L standard.

21. The New York Health Department and the EPA are in possession of almost 77,000 household observations about basement radon, gathered as part of the state's radon testing database. The author's request under the state Freedom of Information Law to access a portion of this data to further this research project was adamantly refused by the Health Department and reaffirmed by EPA on grounds of confidentiality.

22. The method of estimation is cross-section ordinary least squares. Although the number of cancer deaths covers the period 1993-1997, only the cumulated sum is used. The reported Breusch-Pagan statistic indicates that the hypothesis of homoscedastic error variance is not rejected. Thus, the most common cross-section regression problem, heteroscedastic (nonconstant) error variance is not present. A log-linear model was also estimated. It had a much lower $R^2 = 0.34$ than the model in Table 6, only two coefficients were significant, and heteroscedasticity was detected using the same Breusch-Pagan Test (Econometric Software, 1995).

23. A Monte Carlo simulation of these results was performed using the relevant coefficients and standard errors from the risk and compliance cost regressions to model uncertainty. Each was assumed normally distributed, in keeping with the underlying least squares regression. The simulation mean cost of saving a life is $938,000, with a minimum of $611,000 and maximum of $2,140,000 (Palisade Corporation, 1997).

24. Direct comparison is difficult because the national distribution of radon is likely to differ from that of the 29 systems under consideration here. However, the Appalachian region, which includes the states along the east coast from New York to Florida, has a mean radon level of 1,127 pCi/L, virtually the same as the 1,106 of the sample of 29 (EPA, 1999, p. 40). Both means are unweighted averages across all system sizes.

25. Although not explained in the report, the Health Department's estimate of 2,000 wells requiring remediation appears to be based on the 5,331 groundwater wells statewide multiplied by a 37% occurrence rate in excess of 500 pCi/L in the wells sampled. Because about 50% of wells sampled exceeded 300 pCi/L, it follows that about 2,700 wells need attention at that regulatory standard.

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