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Office of Water
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REPORT TO THE UNITED STATES CONGRESS ON RADON IN DRINKING WATER

MULTIMEDIA RISK AND COST ASSESSMENT OF RADON

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OVERVIEW

Radon, a naturally occurring gas, is colorless, odorless, tasteless, chemically inert and radioactive. People are exposed to radon primarily in their homes from radon gas seeping up from the soil. People can also be exposed to radon by drinking tap water or by inhaling radon released into indoor air from tap water used for showering, washing, or other domestic uses, or when the water is stirred, shaken, or heated before being ingested. Radon is second only to cigarette smoking as a leading cause of lung cancer in the United States.

In 1992, Congress directed EPA to report on the risks from exposure to radon, the costs to control this exposure and the risks from treating to remove radon. This report presents the findings in response to that Congressional directive. The following table is a summary of EPA's risk estimates, cancer cases avoided and costs for both air and water.

Summary of EPA's Estimates of Risk, Fatal Cancer Cases, Cancer Cases Avoided, and Costs for Mitigating Radon in Water and Air

	Drinking Water	Indoor Air
Number of Fatal Cancer Cases per Year*	192*	13,600
Proposed Level or Target Level	300 pCi/L_{water}	4 pCi/L_{air}
Individual Lifetime Risk of Fatal Cancer at Target Level	2 in 10,000	1 in 100
Total Number of People Above Target Level	19 million	15 million
Number of Fatal Cancer Cases Avoided Annually by Meeting the "Target" Level	84	100 (2,200)**
Total Annual Cost for Mitigating Radon	$272 million	$1,504 million

* Includes those exposed above and below the target level in community ground water systems only.

** The voluntary air program is estimated to have avoided 100 fatal cancer cases per year based on 1992 data. Annual lung cancer cases averted by the voluntary air program are expected to increase each year as additional mitigations occur and new construction is built to be radon resistant. The air program has the potential to avert 2,200 cancer cases per year assuming 100% voluntary monitoring and mitigation.

EPA estimates that approximately 19 million people are exposed to a radon level above the proposed drinking water standard, or Maximum Contaminant Level (MCL), of 300 pCi/L_{water}. Approximately 2 of every 10,000 individuals exposed at 300 pCi/L would develop a fatal case of cancer as a result of exposure to radon at this level. Approximately 15 million people are exposed to airborne residential radon at levels above EPA's voluntary indoor air action level of 4 pCi/L_{air}. The 4 pCi/l action level is equivalent to a water exposure level of 40,000 pCi/l. It is estimated that approximately 1 in every 100 individuals could suffer lung cancer deaths as a result of exposure to radon at this level.

The total annual cost to treat radon in drinking water is $272 million. The regulated industry has estimated higher costs than EPA. The American Water Works Association (AWWA) estimated national costs at $2.5 billion per year. The Association of California Water Agencies (ACWA) estimated annual costs of $ 520 million for California alone. The major differences in Agency and industry cost estimates result from differences in the number of water systems affected by the proposed standard, differences in the treatment costs that would be incurred by a typical public water system to comply with the proposed standard, and the interest rate charged for the purchase of treatment equipment. The biggest differences are in treatment costs. EPA has modified its original cost estimates in response to industry comments. For example, EPA's revised cost estimates recognize that many public water systems relying on ground water will need to disinfect the water once they draw it out of the ground to aerate it. The revised costs also recognize that most ground water systems rely on more than one well and, therefore, need to install treatment at more than one location. Industry's estimates are more typical of additional costs likely to be incurred by large systems (e.g., higher labor rates in urban areas and more engineering design work rather than purchase of off-the-shelf designs). Although each party's estimate of the cost of a treatment technology may be reasonable in and of itself, EPA believes its estimates better reflect likely industry practice for the small systems which are most affected by the rule.

As required by Congress, the Science Advisory Board (SAB) reviewed EPA's study. The SAB noted the cost differences discussed above and also noted that EPA had employed a reasonable approach to the analysis of occurrence data, technologies, and costs as a function of system size. In response to earlier SAB concerns about uncertainties in the radon risk assessment, EPA conducted a quantitative uncertainty analysis of the risks associated with exposure to radon in drinking water. While noting some uncertainties continue in the risk assessment, the SAB committee reviewing this analysis cited it as "state of the art". The uncertainty analysis is more explicit for radon now than for any previous rule, not because of any greater uncertainty in these estimates but in response to the SAB's request and EPA's decision to present uncertainty more explicitly in future rulemaking.

The cancer risks from radon in both air and water are high. While radon risk in air typically far exceeds that in water, the cancer risk from radon in water is higher than the cancer risk estimated to result from any other drinking water contaminant. This report is the most comprehensive assessment to date on radon exposure and risk and forms a sound foundation for policy decision-making.

SUMMARY OF FINDINGS

EPA prepared this report in response to the Congressional mandate in Public Law 102-389 (the Chafee-Lautenberg Amendment to EPA's Appropriation Bill, enacted October 6, 1992) which directs the Administrator of the U.S. Environmental Protection Agency (EPA) to report to Congress on EPA's findings regarding the risks of human exposure to radon, the costs for controlling or mitigating that exposure, and the risks posed by treating water to remove radon.

The Chafee-Lautenberg Amendment called for an explicit multimedia comparison of the risks from radon in indoor air and drinking water. In EPA's Appropriation Bill, Congress required EPA to (1) report on the risk of adverse human health effects associated with exposure to various pathways of radon; (2) report on the costs of controlling or mitigating exposure to radon; (3) report on the costs for radon control or mitigation experienced by households and communities, including the costs experienced by small communities as the result of such regulation; (4) consider the risks posed by the treatment or disposal of any waste produced by water treatment; (5) have the Science Advisory Board review the EPA's study and submit a recommendation to the Administrator on its findings; and (6) report the Administrator's findings and the Science Advisory Board's recommendations to the Senate Committee on Environment and Public Works and the House Committee on Energy and Commerce.

Congress placed these requirements on the Agency because of the concern voiced in the United States over the costs to be incurred by public water systems in the control of radon in drinking water while a larger threat from indoor air was not being addressed except through voluntary measures. Amendments to the Safe Drinking Water Act in 1986 called for the regulation of radon in drinking water.

Radon, a naturally occurring gas, is colorless, odorless, tasteless, chemically inert and radioactive. People can be exposed to waterborne radon either by ingestion or inhalation. When ingested, radon is distributed throughout the body, which increases the cancer risk to many organs. Radon also is released into indoor air from tap water used for showering, washing, or other domestic uses, or when the water is stirred, shaken, or heated before being ingested. Radon released to the air from water adds to the airborne radon from other sources, increasing the risk of lung cancer.

Radon decay products, or progeny, pose far greater risks than radon gas itself. Therefore, EPA has given them the greatest attention in its analysis of the inhalation risks of radon. The analyses for outdoor radon and residential radon focus on the risks from radon progeny only. The results of those analyses help place the inhalation risks from radon in drinking water in perspective.

People are exposed to waterborne radon in three ways: from ingesting radon dissolved in water; from inhaling radon gas released from water during household use; and from inhaling radon progeny derived from radon released from water. EPA estimates that an individual's combined risk during a lifetime from constant use of drinking water with one picocurie[1] of radon per liter is close to 7 chances in 10 million of contracting fatal cancer.

Many public water supplies use water from ground water wells containing radon, although the concentration of radon in drinking water varies widely. While high radon levels may occur in drinking water from ground water supplies in areas where there are large amounts of underground natural radioactive materials such as radium and uranium, radon levels in surface water typically are very low. Surface water generally lacks a source of radon from rocks, and radon in surface water escapes quickly into the air. Radon levels are determined partly by the geologic formations that store and transport ground water, but also are influenced by the proximity of radioactive elements like uranium that are precursors to radon.

EPA estimates that 81 million Americans obtain their water from community ground water supplies. Based on EPA's analysis of existing data, the population-weighted average radon activity in ground water serving these 81 million people is 246 picocuries per liter of water (pCi/L_{water})(10,000 pCi/L_{water} is equivalent to 1 pCi/L_{air}). Figure 1, on page xi, depicts the portion of individuals impacted at various levels. Radon in water exceeds 100 pCi/L_{water} in 72 percent of the ground water sources surveyed, but these sources serve only 60 percent of the population. The number of small systems impacted is out of proportion to their numbers because they generally rely on ground water, and tend to have higher radon concentrations. Because smaller systems tend to have higher radon concentrations the burden of the costs for mitigating radon in drinking water would weigh more heavily on the small systems. The distribution of systems and population impacted in community ground water systems is illustrated in Figure 2 on page xii.

After a person ingests radon in water, the radon passes from the gastrointestinal tract into the blood, principally by way of the small intestine. The blood then circulates the radon to all organs of the body before it is eventually exhaled from the lungs. When radon and its progeny decay in the body, the surrounding tissues are irradiated by alpha particles. However, the dose of radiation resulting from exposure to radon gas by ingestion varies from organ to organ. The tissues of the stomach, intestines, liver, and lungs appear to receive the greatest doses.

The human health risks from ingesting radon in water depend on the total quantity of radon ingested and the risk factor for ingested radon. The quantity of radon people ingest depends on the volume of water they ingest and the initial concentration of radon in the water. It also depends on the fraction of the radon remaining in the water at the time of ingestion. That amount varies because radon is a volatile gas; it begins to escape from water as soon as the water is discharged from the tap. EPA's estimates of the health risk associated with ingesting radon in drinking water supplied by ground water have taken all of these factors into account. Consequently, calculated estimates of the individual health risk from ingesting radon in water are a product of the *volume* of water ingested that contains radon, the *fraction of radon remaining* in water at the time of ingestion, the cancer *risk factor* (cancer fatality risk per picocurie (pCi) of radon ingested) and the *concentration* of radon in water. To calculate the population risk, total exposed *population* also needs to be taken into consideration.

[1] A curie (Ci) is a standard measure of radioactivity, and a picocurie (pCi) is one trillionth (1×10^{-12}) of a curie.

Assessing the risks from inhaling radon progeny from drinking water requires information on how much of the radon released through household water use enters the air and is converted into progeny that individuals inhale. Given the amount of radon progeny individuals inhale, EPA uses a dose-response factor that estimates the relationship between the radon dose received and the health effects that result. EPA calculated radon risk as a product of the *concentration* of radon in drinking water; a *transfer factor*, which is the relationship between the radon concentration in indoor air derived from water and the initial concentration of radon in water; the *equilibrium factor*, which is the fraction of the potential energy of radon progeny that actually exists in indoor air compared to the maximum possible energy under true equilibrium; the *occupancy factor*, which is the fraction of time individuals spend in their homes, exposed to indoor radon; a *risk factor*, which estimates the risk of lung cancer death from exposure to a given amount of exposure of radon progeny (expressed in working level months); and the *total exposed population*, which is the number of people exposed to the airborne radon progeny resulting from household use of water. The first four factors determine the amount of exposure to radon progeny from drinking water that occurs. The risk factor describes the exposure response relationship between lung cancer deaths and exposure. This factor enables EPA to estimate the risk that can result from a given level of exposure. To calculate the population risk, the total exposed population is also taken into consideration.

Since the time the Proposed Rule was developed and published in July 1991, EPA has used new data on radiation dosimetry and risk to improve the accuracy of the calculations. In terms of lung cancer death (LCD) inhalation risk of radon progeny, EPA revised the dose estimate per pCi/L of radon in air about 30 percent lower based on the dosimetry differences between the mines and homes in the 1991 NAS report Comparative Dosimetry of Radon in Mines and Homes. Also, EPA modified the risk model in estimating the LCD inhalation risk factor based on the recommendation of the Radiation Advisory Committee (RAC) of the Science Advisory Board (SAB). These modifications reduced the LCD risk from inhalation of radon progeny by 38 percent.

The risk for ingested radon has also been revised, based on revised organ-specific risk per unit dose estimates, and additional modifications of intestinal and lung dosimetry treatment. The result was to increase the ingestion risk by a factor of 2.3, mostly because of increased risk estimates of stomach and colon cancers. These new risk estimates are shown in the following table.

Summary of Proposed and Revised Fatal Cancer Risk Estimates for Radon in Water

Exposure Pathway	Lifetime Cancer Risk per pCi/L in Water	
	Proposed	Revised
Inhalation of Radon Progeny Derived from Waterborne Radon Gas	4.9×10^{-7} (74%)	3.0×10^{-7} (45%)
Inhalation of Radon Gas Released from Water to Indoor Air	0.2×10^{-8} (3%)	2.0×10^{-8} (3%)
Ingestion of Radon Gas in Direct Tap Water	1.5×10^{-7} (23%)	3.5×10^{-7} (52%)
Sum of All Pathways	6.6×10^{-7} (100%)	6.7×10^{-7} (100%)

Based on SAB's recommendation, EPA also conducted a quantitative uncertainty analysis of the risks associated with exposure to radon in drinking water. This analysis quantifies the uncertainties in exposure and toxicology and estimates variation in exposure among individuals. This analysis was reviewed by SAB and further expanded in Section 7.1 of the report) based on SAB's recommendations.

The combined lifetime fatal cancer risk per pCi/L in water from all pathways (inhalation of radon progeny due to radon released from water, inhalation of radon gas released from water to indoor air, and ingestion of radon gas in direct tap water) was revised to 6.7×10^{-7} with a credible range of 2.6×10^{-7} to 1.8×10^{-6}. EPA's nominal estimate for the individual lifetime inhalation risk of lung cancer deaths per pCi/L of radon in drinking water is 3.0×10^{-7} with a median of 3.9×10^{-7} and a credible range of 1.4×10^{-7} to 1.4×10^{-6}. EPA's nominal estimate for the individual lifetime ingestion risk of fatal cancers per pCi/L of water is 3.5×10^{-7} with a median of 1.7×10^{-7} and a credible range of 3.7×10^{-8} to 7.4×10^{-7}. The combined lifetime fatal cancer risk per pCi/L in water from inhalation of radon progeny, inhalation of radon gas released from water to indoor air and ingestion of radon gas in direct tap water is 6.7×10^{-7}, with a median of 6.5×10^{-7} and a credible range of 2.7×10^{-7} and 1.8×10^{-6}. These credible ranges reflect an increase of approximately 17 percent over the February 1993 analysis. Lastly, EPA estimated that the individual lifetime fatal cancer risk for inhaling waterborne radon gas is 2×10^{-8} per pCi/L_{water}. Due to the small contribution (3%) to the overall risk, the uncertainty of the risk from inhaling radon gas was not quantified.

The following table shows the number of estimated cancer fatalities per year due to various pathways of radon exposure, based on revised fatal cancer risk estimates and occurrence data. EPA's nominal estimate of total lung cancer deaths caused by inhalation of radon progeny in drinking water, for example, is 86 (median of 113), with a credible range of 40 to 408 per year. EPA's nominal (or most likely) estimate of total fatal cancer cases caused by ingestion of radon in drinking water is 100 (median of 46), with a credible range of 11 to 212 per year.

The threat from radon in drinking water is about half (48 percent) due to inhalation and about half (52 percent) due to ingestion of drinking water. These estimates are for the exposed population served by community ground water systems. Due to the time constraint for completing the report, risk estimates for waterborne radon via various exposure routes and their credible range calculations were only performed for exposed populations served by community ground water supplies and do not include non-transient, non-community (NTNC) ground water supplies (such as schools or hospitals). These calculations suggest that the population risks from radon in drinking water are similar to or higher than currently known risks from most chemical pollutants in drinking water that are now subject to regulation.

Cancer Fatalities per Year due to Exposure to Radon

Exposure Pathway	Lower Estimate	EPA's Nominal Estimate	Upper Estimate
Inhalation due to Radon Treatment	--	--	< 1
Inhalation of Radon* Gas Released from Water to Indoor Air	--	6	--
Inhalation of Radon* Progeny Derived from Waterborne Radon Gas	40	86	408
Ingestion of Radon* in Drinking Water	11	100	212
Inhalation from Outdoor Air	280	520	1,500
Inhalation from Indoor Air	6,740	13,600	30,600

* Estimates due to exposure through community water supplies only.

The following table is a summary of EPA's risk estimates, cancer cases avoided and costs for both air and water. EPA estimates that approximately 19 million people (17.2 million people served by community ground water systems and 1.7 million people served by non-transient, non-community ground water systems) are exposed to a radon level above the proposed drinking water standard, or Maximum Contaminant Level (MCL), of 300 pCi/L_{water}. Figure 3 on page xiii depicts the nominal cases avoided at various radon levels in water provided by community ground water systems only. Approximately 2 of every 10,000 individuals exposed at 300 pCi/L would develop a fatal case of cancer as a result of exposure to radon at this level.

Approximately 15 million people are exposed to airborne residential radon at levels above EPA's voluntary indoor air action level of 4 pCi/L_{air}. It is estimated that approximately 1 in every 100 individuals could suffer lung cancer deaths as a result of exposure to radon at this level.

Summary of EPA's Estimates of Risk, Fatal Cancer Cases, Cancer Cases Avoided, and Costs for Mitigating Radon in Water and Air

	Drinking Water	Indoor Air
Number of Fatal Cancer Cases per Year*	192*	13,600
Proposed Level or Target Level	300 pCi/L_{water}	4 pCi/L_{air}
Individual Lifetime Risk of Fatal Cancer at Target Level	2 in 10,000	1 in 100
Total Number of People Above Target Level	19 million**	15 million
Number of Fatal Cancer Cases Avoided Annually by Meeting the "Target" Level	84**	100 (2,200)***
Total Annual Cost for Mitigating Radon	$272 million	$1,504 million
Average Cost per Fatal Cancer Case Avoided	$3.2 million	$0.7 million
- For largest size systems (serving greater than one million persons)	$1.2 million	N/A
- For smallest size systems (serving between 25 and 100 persons)	$7.9 million	N/A

* Includes those exposed above and below the target level in community ground water systems only.

** Includes cases in non-community systems as well as community systems.

*** The voluntary air program is estimated to have avoided 100 fatal cancer cases per year based on 1992 data. Annual lung cancer cases averted by the voluntary air program are expected to increase each year as additional mitigations occur and new construction is built to be radon resistant. The air program has the potential to avert 2,200 cancer cases per year assuming 100% voluntary monitoring and mitigation.

As noted above, the total annual cost is $272 million to treat radon in drinking water. The following exhibit shows the national cost separated into total capital, annual amortized capital, annual operation and maintenance (O&M), and total annual costs. It is important to note that the regulated industry has estimated higher costs than EPA. The American Water Works Association (AWWA) estimated national costs at $2.5 billion per year. The Association of California Water Agencies (ACWA) estimated annual costs of $ 520 million for California alone. The differences between the estimates are included in chapter 4 of the report. Figure 4 on page xiv depicts the total annual costs for different MCLs. Based on the best revised cost estimates, EPA estimates that the average household cost of radon treatment will range from $242 per household per year in the smallest water systems (i.e., those serving fewer than 100 people) to about $5 per household per year in the largest water systems.

National Costs for Controlling or Mitigating Radon in Water
(millions of dollars*)

Type of Cost	Proposed Estimate	Revised Best Estimate
Total Capital over 20 yrs	$1,579	$1,602
Annual Amortized Capital	106	151
Annual O&M	74	121
Total Annual	180	272

*Cost estimates include community and non-transient non-community systems.

The following exhibit presents the estimates of annual costs for testing and mitigating radon in indoor residential air. EPA's best estimate of the national cost for addressing radon in indoor residential air for a fully implemented voluntary program is $1,504 million annually amortized (the period of time over which a loan will be paid off) over a 74 year period. The amortization period is based on the average life expectancy of the U.S. population and a time period representative of at least the average life of a home. As the table indicates, most of the costs (approximately 75 percent) are in the operation and maintenance of the system, while only 25 percent of the costs are for the testing and initial installation of the mitigation systems.

Annual Cost Estimates for Testing & Mitigating Radon in Indoor Air
(millions of dollars per year)

Type of Cost	Best Estimate
Annualized Testing Costs	$90
Annualized Installation Costs	324
Annualized O&M	1,090
Total Annual Costs	1,504

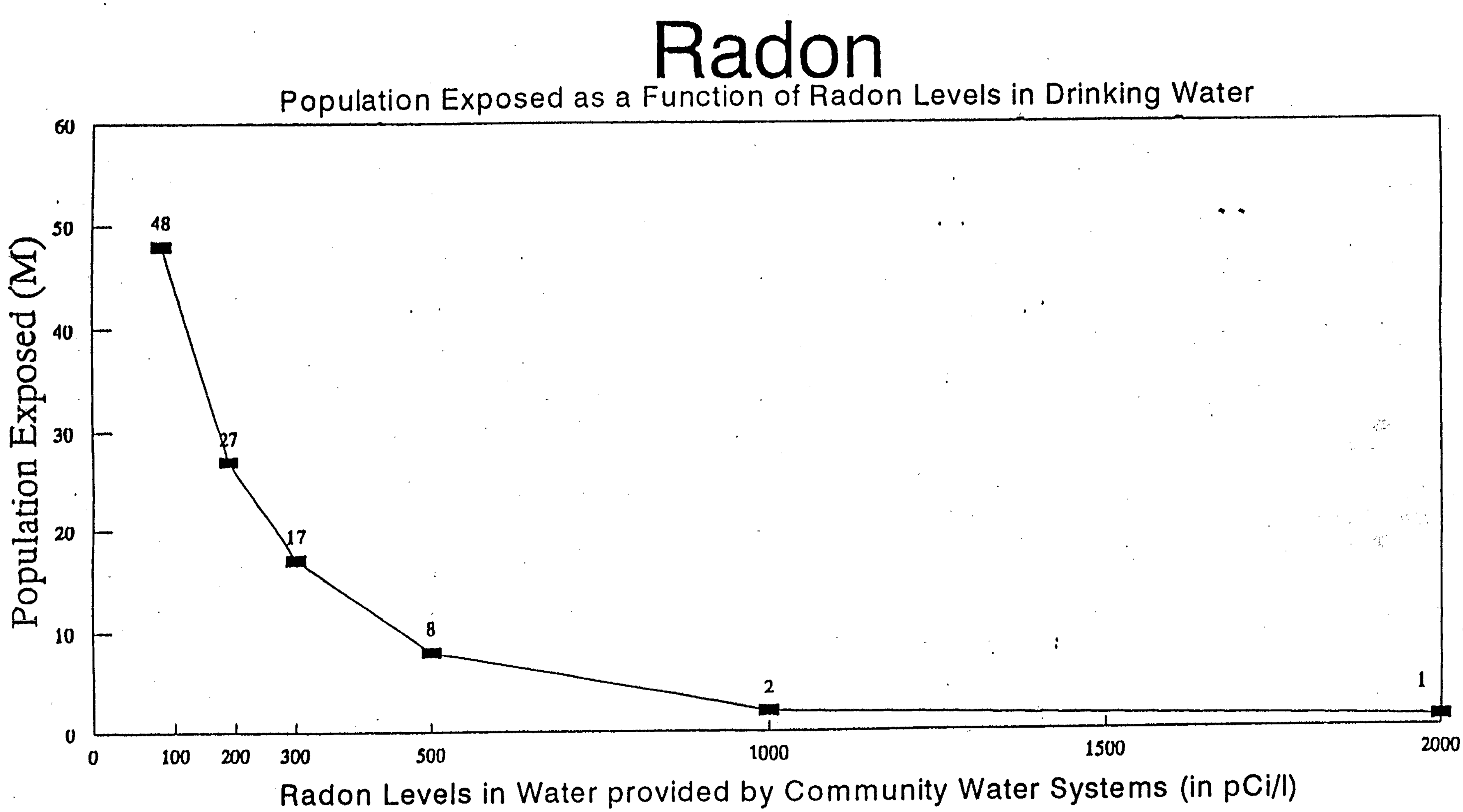
EPA conducted an analysis of the cost per statistical cancer case avoided for different hypothetical levels of regulatory control in community water systems. Community water systems are those which serve residences and comprise the bulk of the water systems which would be affected by an EPA drinking water regulation. (Other systems which would be affected by the rule but which are not included in this analysis are non-transient, non-community water systems, or those which serve facilities such as schools, hospitals, and office buildings.) This analysis is reflected in Figures 3 and 4. For each level of control, Figure 3 shows the estimated number of cases avoided, and Figure 4 shows the estimated total national annual costs. Using 300 pCi/l as an example, the annual number of cases avoided on Figure 3 is 68, while on Figure 4 the total national annual costs associated with 300 pCi/l are estimated to be $202 million. The cost per case avoided is 202 divided by 68, or approximately $3 million. This analysis can be completed for various hypothetical levels of regulatory control.

When all water systems, including non-transient, non-community water systems are considered, the total annual cost of mitigating radon exposure through drinking water is calculated to be $272 million to prevent the deaths of approximately 84 people each year. This is an average of $3.2 million dollars per life saved, as shown in the table on page viii. Based on the total annual cost of mitigating radon exposure in indoor residential air, EPA calculates that it would cost an average of $0.7 million per life saved (or $0.9 million at a 7 percent discount rate) to prevent the deaths of approximately 2,200 people each year due to exposure to radon in residential air.

The combined annual cost estimate is $1,776 million for controlling residential radon from all sources. The component cost estimates for indoor air ($1,504 million dollars per year) and drinking water (272 million dollars per year) are based on a 3 percent and a 7 percent discount rate, respectively. If both the water and air cost estimates were calculated at a 3 percent interest rate the costs would be $230 million per year for water and $1,504 million per year for indoor air. If both the water and air cost estimates were calculated at a 7 percent interest/discount rate the costs would be $270 million per year and $1,980 million per year respectively. The drinking water cost estimate is based on a 20-year amortization period for installation of treatment equipment at public water systems facilities, however, the indoor air cost estimate is based on a 74-year amortization period. Comparing the national costs for air and water is difficult because the air program costs are based on 100 percent compliance with a voluntary program, whereas the cost for water are based on 100 percent compliance for public water systems to meet the requirements of the Safe Drinking Water Act*.

* Most of the costs of mitigating indoor airborne radon are associated with operation and maintenance (O&M) of the systems (75%). The estimates presented throughout the remainder of the document utilize the 3 percent rate which yields an annual cost of $1,504 million for a fully implemented program and a cost per cancer case avoided of $0.7 million.

Figure 1



(Note: Non-Transient, Non-Community Water Systems (NTNCWS) are not included in this graph.)

Figure 2A

Profile of All Community Water Systems (CWS) that exceed 300 pCi/l or greater.

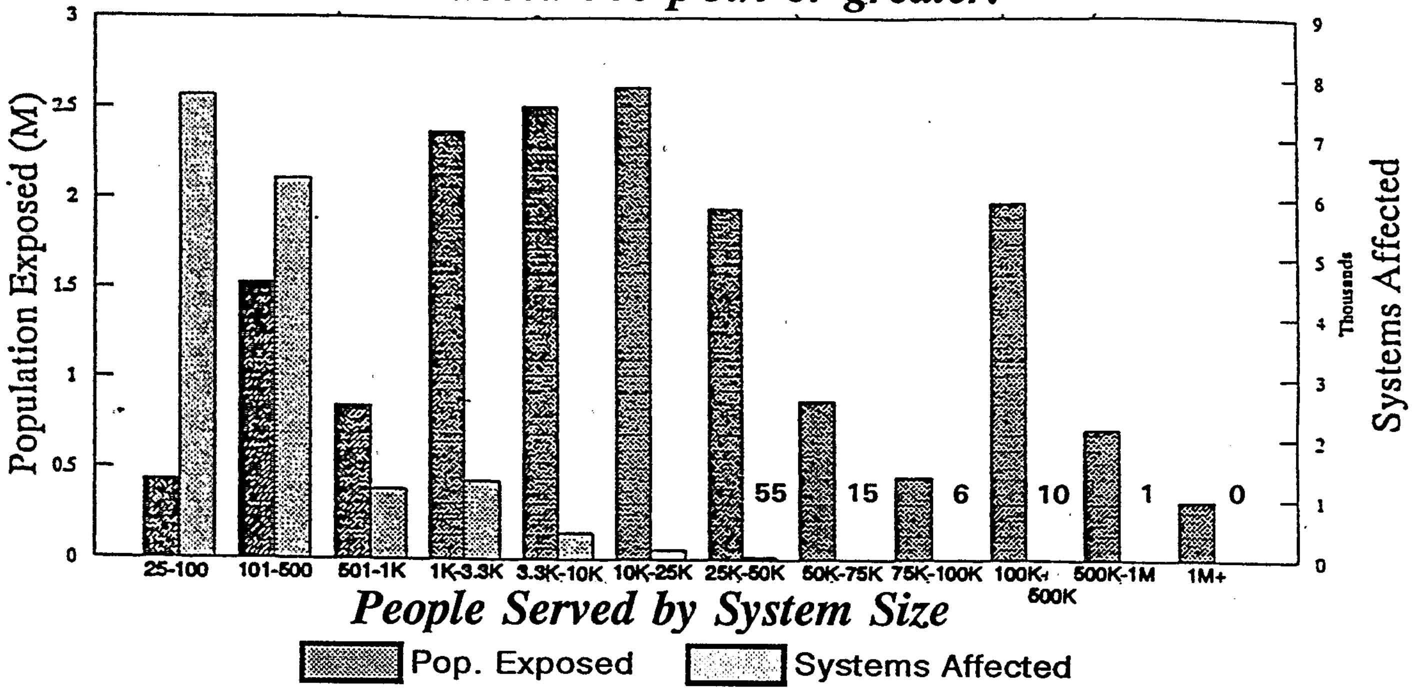


Figure 2B

Profile of All Community Water Systems (CWS)

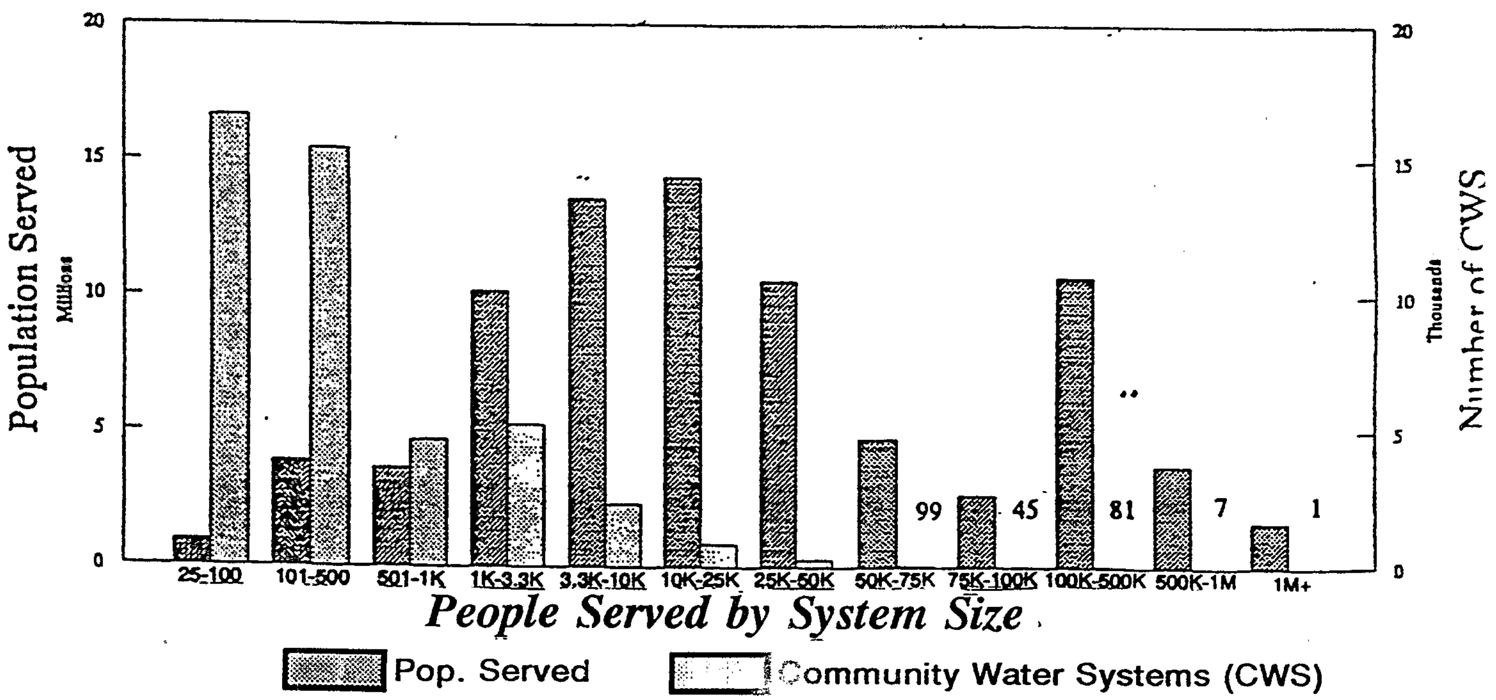
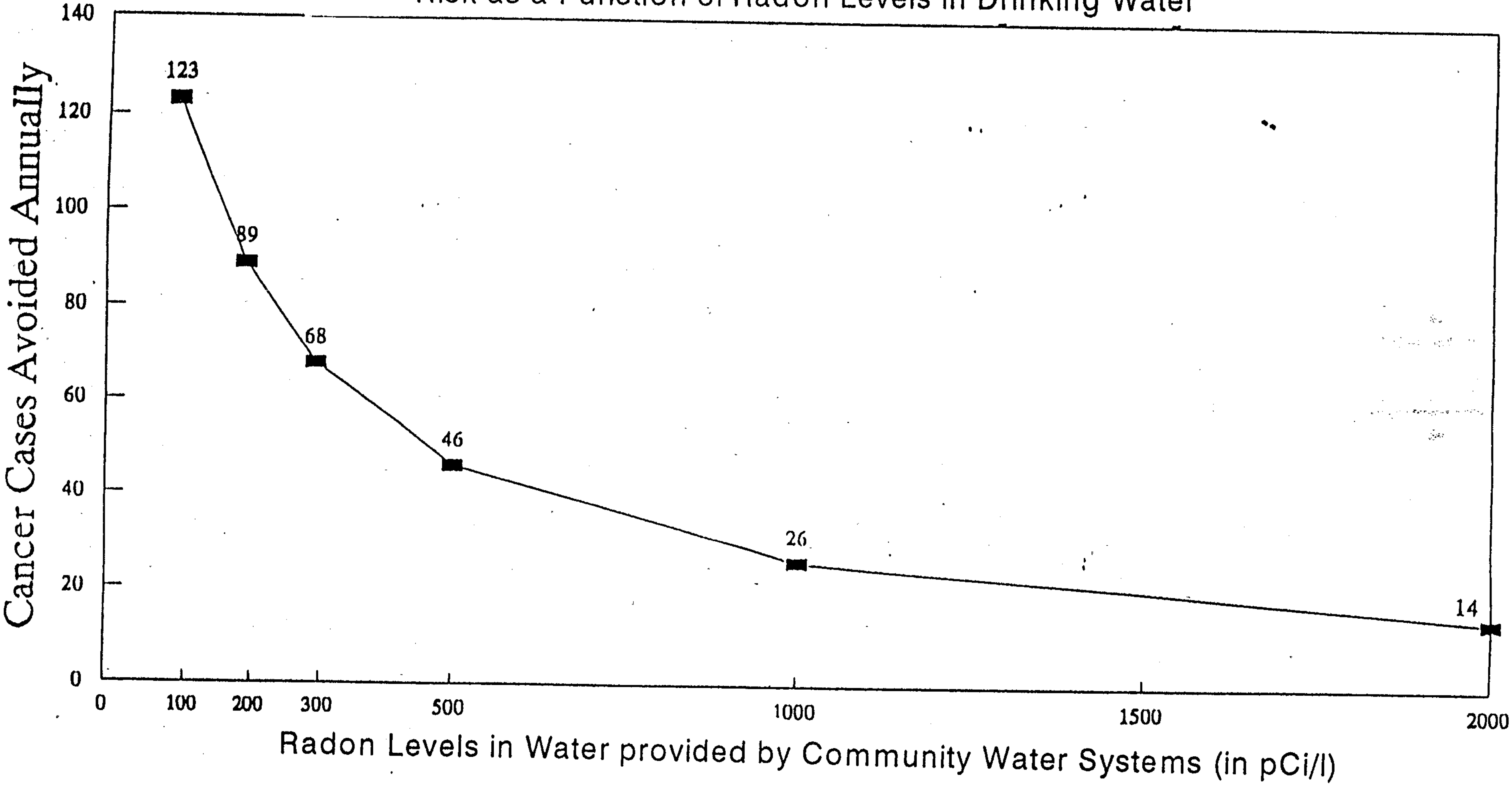


Figure 3

Radon

Risk as a Function of Radon Levels in Drinking Water

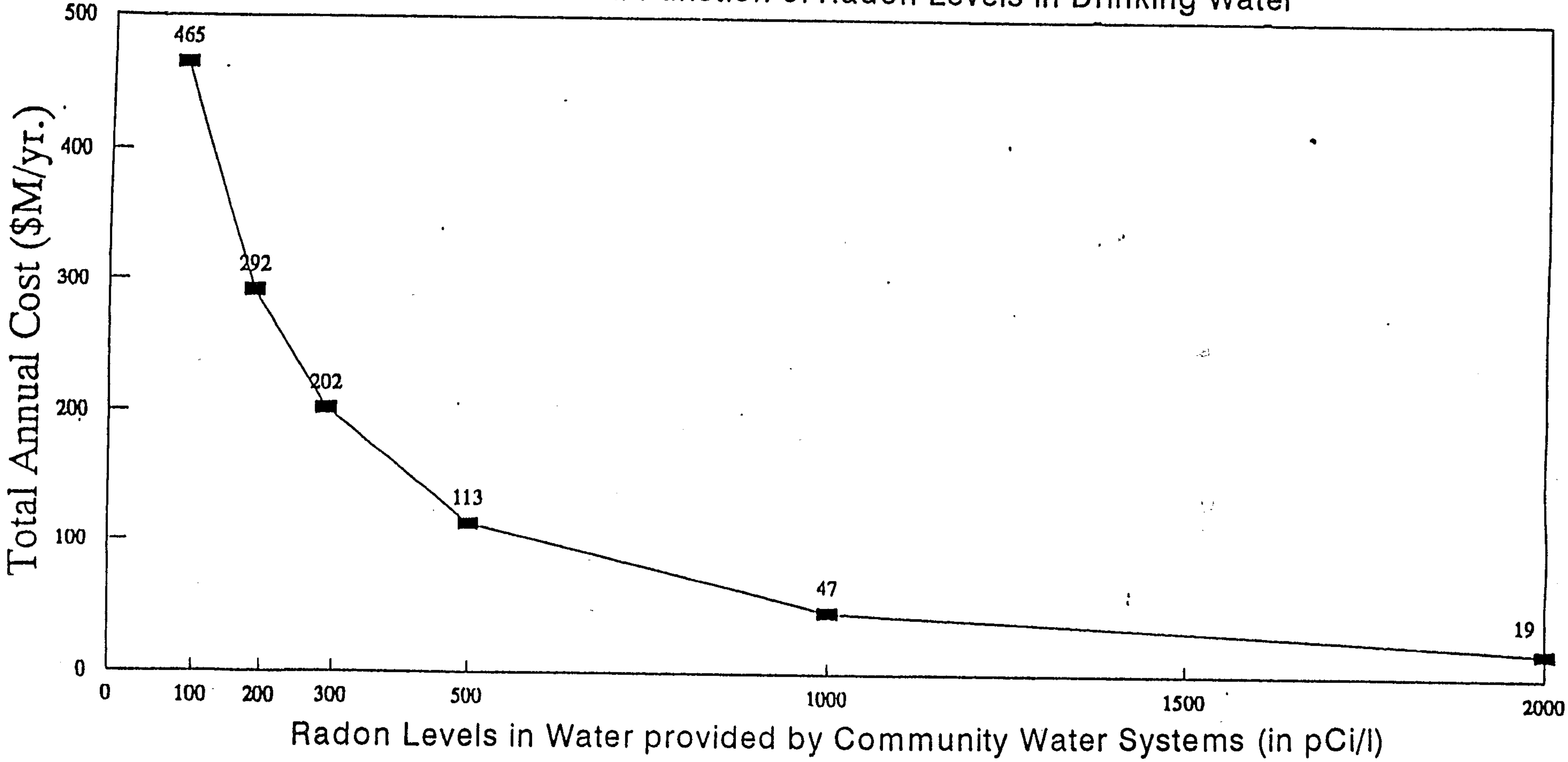


(Note: Non-Transient, Non-Community Water Systems (NTNCWS) are not included in this graph.)

Figure 4

Radon

Annual Cost as a Function of Radon Levels in Drinking Water



(Note: Non-Transient, Non-Community Water Systems (NTNCWS) are not included in this graph.)