A COST-EFFECTIVENESS COMPARISON OF PRIVATE-SECTOR RADON REMEDIATION WITH TRADITIONAL RADIATION PROTECTION ACTIVITIES

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ABSTRACT

Private-sector radon remediation can be well over 100 times more cost-effective than the minimum expenditure of $1000 to avert a whole-body person-rem mandated by the U.S. Nuclear Regulatory Commission for marginal control of exposures to radiation due to effluents from nuclear power plants (10 CFR 50 Appendix I). Using data from the Pennsylvania Department of Environmental Resources (DER) and from Radon Detection & Control (RDC; a commercial radon remediation firm) spanning more than two years, we relate differences in radon concentrations measured before and after remedial action to capital and operating costs. Simple demographic assumptions and concentration-to-collective dose equivalent conversions lead to a quantitative demonstration of the dramatic imbalance in society's valuation of radiation protection by nuclear utilities when compared to that in the home. The DER data show that an effective person-rem can be averted for $3.01 in high-radon houses (104 houses; average, 189 pCi/L; median 112 pCi/L; GSD 2.75), while the RDC data show that an effective person-rem can be averted for $9.41 in more typical houses (201 houses; average 28 pCi/L; median 19; GSD 2.31).

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INTRODUCTION

A basic tenet of public health activities is that limited resources should be used in a way that is most beneficial to the most people. Studies on the value of a human life have demonstrated the great incongruities in how money is spent for increments of health and safety (1, 2). In this paper, we demonstrate that radon remediation activities can be 100 to 300 times more cost effective than radiation protection activities at nuclear power plants required by U.S. Federal regulations (3).

In the case of nuclear power, the risk is perceived as dread, unknown, uncontrollable, imposed, and manageable with someone else's money. In the case of radon exposure in the home, the risk is perceived as less dread, better known, more controllable, voluntarily accepted, and manageable only with one's own money. The traditional perception of the home as a "safe haven" from the ills of the outside world runs counter to the acceptance of a serious radiological risk that may exist from natural (or, rather, technologically-enhanced natural) causes. The public health perspective, however, dictates that society's resources should be refocused on indoor radon, rather than on tiny increments of safety achieved at tremendous cost in controlling effluents from nuclear power plants.

DATA

Two sets of data are used in this study. The first is from the Pennsylvania Department of Environmental Resources (DER) report summarizing the Pennsylvania Radon Research and Demonstration Project (4). This report lists radon concentration data from 104 houses for which measurements before and after remediation were available. The DER data arose from research and development work, and the houses to be remediated had *very* high radon concentrations (many over 200 pCi/L). These data are not a random sample of houses, and remediations were done in the mid-1980s when the technology was in its infancy. Concentration measurements were made using grab or continuous flow-through alpha scintillation measurements. There is no evidence that measurements were made using integrating detectors such as charcoal, diffusion barrier charcoal, or alpha track.

The second set of data are from Radon Detection & Control (RDC). These data included 201 houses remediated between 1987 and 1989, mostly in the Allegheny and Beaver County areas of western Pennsylvania. The RDC data represent a more typical set of radon remediations in that they were done for real estate transactions, for relocation companies, or for health concerns of the occupants. The RDC radon measurements were made using activated charcoal screening detectors[1] exposed for two to four days and processed commercially. In some cases, the concentrations are averages of two or more measurements. The radon concentrations were measured at the same location before and after remediation.

ANALYSIS AND DISCUSSION

The DER data are summarized in Table 1a, while the RDC data are summarized in Table 1b. From left to right, the columns are the initial or "Before" remediation radon

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[1]Key Technology, Inc., P.O. Box 562, Jonestown, PA 17038; or Air Chek, Inc., P.O. Box 2000, Arden, NC 28704.

concentration; the final or "After" remediation concentration; the remediation cost; the percent reduction of radon concentration; the percent reduction in radon concentration per $1000 spent on remediation; the change in concentration; the change in concentration per $1000 spent on remediation; the ratio of the "Before" to the "After" concentrations; and the ratio reduction achieved per $1000 spent on remediation. Note that minimum and maximum entries in different columns may be from different houses; these values were the minima and maxima in the entire data set.

Table 1a. Summaries of the Pennsylvania D.E.R. data (Weston & Simon 1988).

	Radon Conc. Before (pCi/L)	Radon Conc. After (pCi/L)	Remed-iation Cost ($)	% Re-duction	% Re-duction per 1000$ %/k$	Conc. Change (pCi/L)	Conc. Change per 1000$ (pCi/L)/k$	Reduct. Factor	Reduct. Factor per 1000$ (/k$)
No. of houses	104	104	104	104	104	104	104	104	104
Minimum	11.6	0.3	1301	-53.2	-13.0	-62.1	-15.1	0.65	0.16
Maximum	1653.2	178.8	16185	99.9	73.7	1576.2	312.3	893.0	222.9
Mean	189.1	10.6	3729	90.4	29.6	178.5	47.4	112.4	33.3
Std.Dev.	240.2	27.7	2156	23.2	14.2	231.3	49.7	145.0	40.7
Geo. Mean	112.3	2.5	3324	92.7	27.8	107.4	32.3	44.8	13.5
G.S.D.	2.75	4.43	1.57	1.21	1.59	2.91	2.61	4.96	4.98
r^2 (lognorm.)	0.992	0.930	0.966					0.972	

Table 1b. Summaries of Radon Detection & Control data, 1987-89.

	Radon Conc. Before (pCi/L)	Radon Conc. After (pCi/L)	Remed-iation Cost ($)	% Re-duction	% Re-duction per 1000$ %/k$	Conc. Change (pCi/L)	Conc. Change per 1000$ (pCi/L)/k$	Reduct. Factor	Reduct. Factor per 1000$ (/k$)
No. of houses	201	201	201	201	201	201	201	199	201
Minimum	4.2	0.0	150	-2.7	-1.4	-0.3	-0.2	1.0	0.0
Maximum	156.0	18.3	2905	100.0	634.4	155.6	380.7	390.0	421.1
Mean	28.1	2.0	1030	87.3	99.0	26.1	27.7	29.3	30.3
Std.Dev.	29.0	2.4	325	15.8	63.4	28.4	37.3	46.8	52.9
Geo. Mean	19.2	1.3	957	86.1	90.3	16.6	17.4	14.5	15.4
G.S.D.	2.31	2.53	1.55	1.24	1.47	2.59	2.50	3.21	2.97
r^2 (lognorm.)	0.969	0.993	0.862					0.997	

Under each column are the number of houses used in that column; the minimum, maximum, arithmetic mean, and standard deviations of each quantity; and the geometric mean and geometric standard deviations (GSD; dimensionless) of the quantities. For the DER data, the geometric means and GSDs for the difference, % reduction, concentration change per $1000, and percent per $1000 were calculated from 101 data pairs, omitting the 3 negative values. For the RDC data, geometric means and GSDs were calculated from 197 to 199 non-negative values for those columns with negative entries, or, in the case of the ratio, with zero final concentration.

The DER houses had larger average initial ("Before" remediation) concentrations than did the RDC houses, with arithmetic means of 189 ± 240 and 28 ± 29 pCi/L, respectively. This is due to the different selection processes, and to the fact that many of the DER houses were in the Reading Prong area of southeastern Pennsylvania, a region with exceptionally high indoor radon levels. Both data sets showed lognormal distributions, as seen in Figures 1 and 2, with geometric means of $112 \stackrel{\times}{\div} 2.75$ ($r^2 = 0.992$) and $19 \stackrel{\times}{\div} 2.31$ ($r^2 = 0.969$). Lognormal fits were done by the LPROBIT code using Finney's weighting method (5).

The maximum in the DER data set, 1653 pCi/L, was more than ten times higher than the maximum in the RDC data set, 156 pCi/L. The minimum "Before" value (i.e., 4.2 pCi/L) in the RDC data may indicate the force that the real estate and relocation companies have on radon remediation decisions.

Final ("After" remediation) concentrations averaged 10.6 and 2.0, respectively, for the DER and RDC data. The lower final concentration for RDC is understandable in light of the fact that they usually guarantee a concentration below 4 pCi/L, and usually continue to remediate until the concentration is below this level. Again, both data sets showed lognormal distributions, with geometric means of $2.5 \stackrel{\times}{\div} 4.43$ ($r^2 = 0.930$) and $1.3 \stackrel{\times}{\div} 2.53$ ($r^2 = 0.993$). The wide GSD, 4.43, for the DER data, along with its moderate deviation from lognormality may reflect the varying conditions applied to remediation during the DER's research and development process.

The DER data show significantly higher average remediation costs than the RDC data: \$3729 ± \$2156 vs. \$1030 ± \$325. The geometric means were $\$3324 \stackrel{\times}{\div} 1.57$ ($r^2 = 0.97$) vs. $\$957 \stackrel{\times}{\div} 1.55$ ($r^2 = 0.86$). These numbers are understandable in light of the differing nature of the two endeavors: the DER project was a research and development activity, done to develop technologies; the RDC work is done commercially in a competitive atmosphere, and benefits from well-established practices in remediation.

We chose three ways of looking at the data: *percent reduction, concentration change*, and the *reduction factor*. The percentage reduction is the difference in radon concentrations divided by the "Before" concentration, expressed as a percent; the concentration change is simply the difference between "Before" and "After" concentrations; and the reduction factor is the ratio of the "Before" to "After" concentrations. All three methods are somewhat flawed because no concurrent long-term background concentration measurements were available. Since indoor radon levels cannot be reduced below ambient outdoor levels using any of the remediation methods employed for DER or by RDC, both percent reduction and reduction factor have values limited by background concentration. The limits are unimportant for high initial concentrations, but can restrict measures of success when starting from lower concentrations.

The *percentage reduction* summaries are given for each data set in Table 1. The means are 90.4% for the DER data, and 87.3% for the RDC data. The mean percentage reduction is a somewhat misleading statistic, since its maximum value is 100, with many houses very near this value. The mean *percentage reduction per \$1000* spent on remediation is 29.6%/\$1000 for DER vs. 99.0%/\$1000 for RDC, which primarily reflects the different average remediation costs.

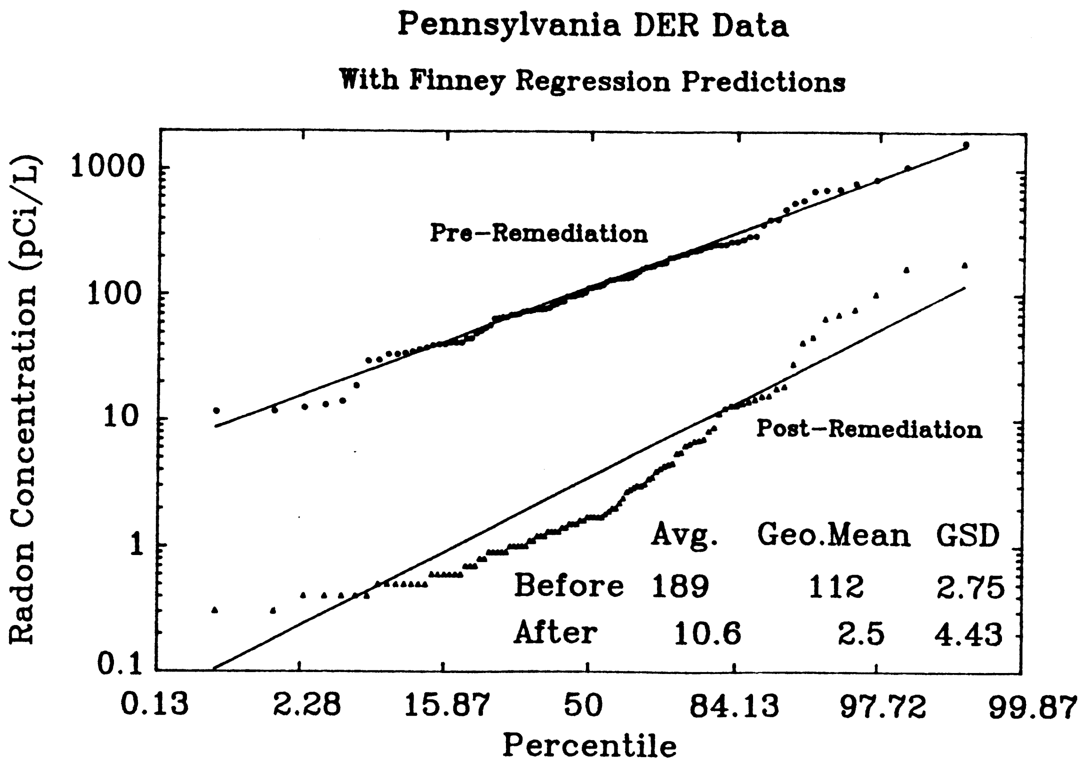

Figure 1. Log-probability plot of "Before" and "After" radon concentrations in 201 houses remediated by Radon Detection & Control, with Finney-weighted regression lines.

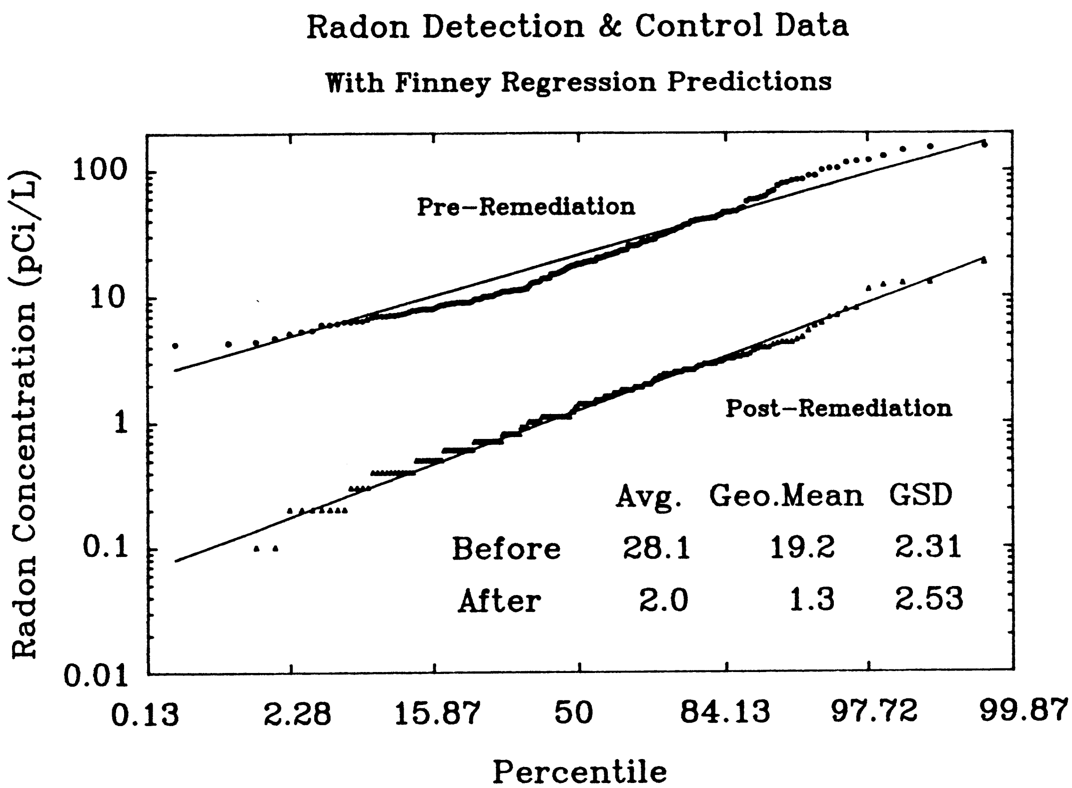

Figure 2. Log-probability plot of "Before" and "After" radon concentrations in 201 houses remediated by Radon Detection & Control, with Finney-weighted regression lines.

The *concentration change* summaries show arithmetic means of 179 ± 231.3 pCi/L for the DER data and 26.1 ± 28.4 pCi/L for the RDC data, the difference largely reflecting the fact that the DER houses had higher concentrations to begin with. The geometric means were 107 pCi/L $\stackrel{\times}{\div}$ 2.91 and 16.6 pCi/L $\stackrel{\times}{\div}$ 2.59, respectively. The mean *concentration change per $1000* was 47 ± 49 [pCi/L]/k$ and 28 ± 37 [pCi/L]/k$ for the DER and RDC data, respectively, indicating that, while the concentration changes in the DER work averaged nearly 7 times greater than the RDC work, the remediation cost per unit concentration change averaged only 1.7 times greater for the DER work. Note that this analysis does not include operating and maintenance costs.

Perhaps more interesting than the percentage reduction is the *reduction factor*. Reduction factors as great as 893 were achieved in the DER program, and 390 in the RDC work. Average reduction factors were 112 and 29, respectively, with geometric means of 45 $\stackrel{\times}{\div}$ 4.96 (r^2 = 0.972) and 29 $\stackrel{\times}{\div}$ 3.21 (r^2 = 0.997), indicating both more vigorous remediation efforts in the DER demonstrations and the limiting effects of ambient radon concentrations when remediating houses with initially low radon levels. Of great interest are the mean *reduction factors per $1000* spent on remediation: these were 33/$1000 and 30/$1000 for DER and RDC, respectively, with geometric means of 13.5/$1000 and 15.4/$1000, indicating that the work was quite comparable in terms of cost-effectiveness when expressed in terms of reduction factors!

The dose equivalent averted through remediation is directly proportional to the concentration change. To evaluate the overall cost-effectiveness of the two remediation projects, we summed the "Before" and "After" concentrations, as well as the costs, as shown in Table 2. These concentration sums can be considered as "Collective Concentration" by analogy with "Collective Dose" and "Collective Dose Rate" as defined by the International Commission on Radiological Protection (6).

Table 2. Sums of concentrations and costs, with analysis statistics for PA D.E.R. and RD&C data.

	Sum of Radon Conc. Before (pCi/L)	Sum of Radon Conc. After (pCi/L)	Sum of Remed-iation Costs ($)	Overall % Re-duction	Overall % Re-duction per 1000$ %/k$	Overall Conc. Change (pCi/L)	Overall Conc. Change per 1000$ (pCi/L)/k$	Overall Reduct. Factor	Overall Reduct. Factor per 1000$ (/k$)
PA D.E.R.	19664	1102	387797	94.4	25.3	18562	47.9	17.8	4.8
R.D.&C.	5649	402	206936	92.9	90.2	5248	25.4	14.1	13.7

The columns in Table 2 that begin with the word "Overall" differ from the mean or geometric mean values presented in Table 1 because they are computed only from the sums given in Table 2, rather than from the actual distributions. The overall percent reduction in each data set (94.4% and 92.9%, respectively, for DER and RDC) is *greater* than the mean because greater reductions were achieved in high initial concentration houses than in low concentration houses. The percent/$1000 values (25% and 90%) are based on the mean remediation costs in Table 1, and are *lower* than the means in that table.

The collective dose equivalent averted by remediation is proportional to the overall concentration change, which was 18562 pCi/L for the DER work and 5248 pCi/L for the RDC remediations. While the DER overall concentration change is 3.5 times higher than the RDC change, the cost-effectiveness value for DER is only 1.9 times that for RDC (47.9 vs. 25.4 [pCi/L]/$1000) based on average remediation costs from Table 1.

The overall reduction factors were 17.8 and 14.1, respectively, for DER and RDC, while the reduction factor per $1000 values were 4.8/$1000 and 13.7/$1000, indicating an almost three-fold better investment with the later work when viewed in these terms.

Rather than dealing with risk, as the DER report does, we compute the effective dose equivalent averted by remedial actions, and compare the cost per unit effective dose equivalent averted by remedial actions. The many assumptions needed to do this are summarized in Table 3. We calculate 1.93 lung-rems (to an adult) from a 1-year exposure to a concentration of 1 pCi/L of radon from the product (1 WL/[200 pCi/L])(8766 hours/environmental year)(1 occupational month/170 hours)(0.75 fraction of time spent at home)(0.5 rad/WLM)(20 rems/rad = Quality Factor for alpha radiation). *Effective* dose equivalent rate per unit concentration (0.23 effective rems/([pCi/L]-year) is obtained by multiplying by the ICRP weighting factor for the lung (6), i.e., w_{lung} = 0.12.

Table 3. Assumptions used in calculating the expenditure per person-rem.

200	[pCi/L]/WL, i.e., 50% equilibrium
0.5	rad/WLM (ref. 7)
20	Q (rem/rad; ref. 6)
0.12	w_{lung}, i.e., effective rem per lung rem (ref. 6)
0.75	fraction of time spent at home
8766	hours/environmental year
170	hours/occupational month
4	persons per house
10	years life expectancy for radon control system
125	$/year energy penalty (ref. 11, modified)
29	Watt fan[a]
0.10	$/kWhr[b]
1.93	lung rems/([pCi/L]-year)
0.23	effective rems/([pCi/L]-year)
62.7	effective microsieverts/([Bq/m^3]-year)
25.42	$/year, fan operation cost

[a] Dayton Electric Mfg. Co., 5959 W. Howard St., Chicago IL 60648; Model 4C720.
[b] Duquesne Light Co., Pittsburgh, PA; 1989

The value of 0.5 rad/WLM is taken from Harley and Cohen (7), and is probably an underestimate of the conversion for children (8, 9), for which estimates as high as 1.2 rad/WLM are available (8). Additionally, the value of 0.75 of one's time in the house is somewhat higher than the values of 0.64 to 0.73 used by some at the EPA (10); however, the EPA work is based on data which dramatically under-represent infants, small children, and the elderly.

Additionally, we assume that there are 4 persons per house, and a ten-year life expectancy for the remediation system. We further assume $125/year for operating costs and the cost of loss of conditioned air. Due to the use of a 29 W fan by RDC, rather than the more common 90 W fan, we have lowered our estimate of annual costs below the $150 estimated by Henschel (11). It is important to point out that the annual cost is not well known, and is limited at the lower end by the fan operation cost ($25.42), but may be much greater than our estimate in some cases.

A critical assumption in our calculations is that the change in radon concentrations are representative of the air that house occupants actually breathe. We do not know the proportion of houses for which this is the case. In some cases, the radon measurements are simply screening values measured in the lowest livable area of a house; in other cases, they are representative measurements of air that the occupants breathe. If a ratio for basement concentration to first floor concentration of 2.5 is used (12), then our calculated average cost per (unit collective effective dose equivalent [CEDE] averted) could be multiplied by no more than this factor.

The average cost per unit CEDE averted is tabulated in Table 4. The remediation cost plus the operation and maintenance costs are added to yield totals of $4979 for the DER work and $2280 for the RDC remediations. Average concentration changes are multiplied by 0.23 effective rem per ([pCi/L]-year) and multiplied by 4 persons and 10 years to get the 10-year CEDE averted values of 1657 person-rems per house for the DER houses and 242 person-rems for the RDC houses. These values, divided by the total 10-year cost, give the average cost per unit CEDE averted, in dollars per person-rem. The values for the DER and RDC houses are $3.01/person-rem and $9.41/person-rem, respectively.

Table 4. Average cost per unit collective effective dose equivalent averted in radon remediation and as required of the nuclear power industry.

	Cost of 10-year Energy Penalty	Capital Outlay	Total	Average Rn Conc. Change (pCi/L)	10-year CEDE[a] Averted (person-rems /house)	Average Cost per unit CEDE[a] Averted ($/person-rem)
PA D.E.R.	$1250	$3729	$4979	178.5	1657	$3.01
This Study	$1250	$1030	$2280	26.1	242	$9.41
10 CFR 50[b]						$1000.00
10 CFR 50[c]						$33333.33

[a] Collective Effective Dose Equivalent
[b] (App.I Sec.II.D.; whole body)
[c] (App.I Sec.II.D.; thyroid)

The U.S. Nuclear Regulatory Commission has set values of $1000 per whole body rem and $1000 per thyroid rem as the *minimum* amounts that must be expended to limit offsite releases of radioactivity by nuclear power plants (3). The latter value can be converted to effective dose equivalent by dividing by the ICRP risk-based weighting factor for the thyroid, i.e., 0.03, giving $33,333.33. The NRC cost per unit CEDE averted values are roughly 300 and 10,000 times greater than the DER values, and 100 to 3,000 times the more realistic RDC values. Clearly, these numbers are inconsistent.

If a cancer fatality rate of 2×10^{-4} per person-rem is assumed, dollar values to save a human life can be computed. These are $15,000 and $47,000 for the DER and RDC remediations, and $5,000,000 and $167,000,000 for the NRC release limits. The radon remediation costs are in line with other common societal expenditures for life saving (1,2), but the NRC values are not.

CONCLUSIONS

By analyzing two sets of radon remediation data, we have shown that remediation can be a cost-effective activity when compared to other life-saving measures in our society. Expenditures in other areas of radiation protection, such as those required of nuclear power plants by the U.S. Nuclear Regulatory Commission, can be hundreds or even thousands of times less cost-effective.

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