CONTROLLING INDOOR RADON: CURRENT PRACTICE AND FUTURE OUTLOOK

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ABSTRACT

Radon is the most significant health threat from indoor air pollution, causing an estimated 5,000 - 15,000 lung cancer deaths per year in the U.S. A popular misconception is that tight, energy-efficient housing is largely responsible for this natural hazard. However, the concentration of indoor radon (and indoor air pollutants in general) is determined primarily by the strength of the pollutant source. This fact suggests that the most effective way to reduce exposures to indoor radon would be through source controls rather than dilution of indoor pollution through general ventilation.

This paper reviews the status of radon mitigation in the U.S., focusing on two control approaches: soil ventilation, a source-specific control measure, and house ventilation. These two approaches are compared using data from several recent field demonstration projects. It is shown that soil ventilation is the more effective control technique. Soil ventilation reduces indoor concentrations below recommended levels regardless of source strength (initial indoor concentration). House ventilation is a successful control measure when pre-mitigation concentrations do not exceed 10 pCi/l. In addition to their superior performance, soil ventilation techniques are less expensive than general house ventilation, require less maintenance, and are less prone to interruption by residents.

The success to date of radon mitigation work has been largely a result of the professional skill of the researchers completing these demonstration projects. Much more research on these and other control strategies is necessary before these measures will be available for successful widespread applications. Certification of interested contractors is recommended to protect the public as the need and demand for remedial work increases. Mitigating air quality problems in housing may become an extension of the energy house doctor's repertoire, and some may find it profitable to become "indoor air quality specialists".

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INTRODUCTION

Indoor air pollution is considered by some to be the end of innocence for energy conservation. Indoor air quality (IAQ) has received increasing press coverage in the past 5 years, and virtually all references to this subject implicate energy conservation as a principal cause of IAQ problems [1]. The basis of concern is that one aspect of energy efficiency in buildings -- house tightening to reduce infiltration -- may allow air pollutants to accumulate to unacceptable levels.

In fact, results from several recent field studies show that weatherization is not to blame for poor air quality, nor do new, energy-efficient buildings suffer greater air pollution problems than existing, conventional housing [2]. It is becoming clear that indoor air pollution is not a problem for energy-efficient dwellings. Rather, efficient construction with attention to pollutant sources can result in healthier air quality in energy-efficient homes than in leakier homes [2].

The most important determinant of indoor air quality is the strength of pollutant sources. While residential air exchange rates vary by a factor of 10, the rate at which pollutants are emitted into the indoor air can vary by a factor of 100 or more [3]. We also now know that a building's air exchange rate itself can affect pollutant entry or emission rates [4].

As our understanding of the dynamics of indoor air pollution improves, attention is shifting to techniques to reduce indoor exposures. There are five general control approaches: source avoidance, source modification, local ventilation, whole-house ventilation, and air cleaning. Source-specific controls (avoidance and modification) are largely preventive measures, as they reduce the entry of pollutants into the air. Source controls may take the form of chemical or physical modifications, substitution of a benign product or material for one that emits unwanted contaminants, or the outright removal (without substitution) of the offending source.

Ventilation and air cleaning strategies, on the other hand, are reactions to an ongoing problem. They do not reduce the occurrence of pollution, rather, they only reduce the likelihood of human exposure. The energy penalty from increased ventilation is significant -- the 20-40% of the heating and cooling costs lost via infiltration are

exactly why house tightening is practiced in the first place. New ventilation technologies, such as air-to-air heat exchangers and other heat recovery ventilators, reduce the energy penalty associated with ventilation but at a significant capital cost. Of course, some minimum amount of ventilation is needed in all buildings to replace the air polluted with odors, moisture, and the low level contaminants resulting from normal human occupancy, and heat recovery as a component of ventilation is desirable whenever cost-effective.

Since reduced air exchange rates do not necessarily lead to an IAQ problem, it would follow that ventilation is not capable of eliminating pollution from strong sources. At what strength of a pollutant source is increased ventilation an inadequate control? Are more effective source controls available at a lower cost? Reports on the success of individual control measures frequently appear in the literature, but comparisons between different approaches have not been made.

This paper presents a test of principle between indoor air pollution source controls and house ventilation. Radon provides an interesting test case for a comparison of control strategies. Except for the isolated cases where uranium-contaminated soil was used as backfill around housing, the source of radon cannot be removed from the site. Source controls must therefore take the form of modifications to the soil or foundation through which the radon enters. Several researchers have suggested that increased house ventilation may be sufficient to achieve acceptable indoor concentrations when initial radon levels are relatively low; some do not specify what is meant by 'relatively low', while others suggest 15-20 pCi/l [5]. A systematic review of the mitigation results to date has not been performed. This analysis will provide a comparison of the use of source-specific controls and increased ventilation for mitigation of high levels of indoor radon.

INDOOR RADON

Radon is a decay product of radium in the uranium decay chain. Radon enters housing primarily from the soil through cracks and openings in foundations [6]. This gas is undetectable by the human senses, and its presence in housing has been largely unnoticed until about ten years ago. Mortality data of uranium mine workers demonstrates that radon (primarily its decay products, or progeny) causes lung cancer.

The distribution of indoor radon in the U.S. is lognormal with a geometric mean (median) of about 1 pCi/l; the typical outdoor concentration is 0.2 pCi/l [7]. Approximately 5-10% of the U.S. housing stock contains radon in excess of 4 pCi/l, and an estimated 1-3% exceed 8 pCi/l [7]. Lifetime exposure to 1 pCi/l has been estimated to increase the risk of lung cancer by 0.25% [8]. Nationwide, it is estimated radon is the cause of about 9,000 lung

cancers per year, and the risk to occupants of the houses exceeding 8 pCi/l comprises 10-30% of this total risk [7].

The personal risks posed by radon are larger than many "voluntary" hazards for which we take protective action, and much larger than virtually all "involuntary" hazards for which governments take action to limit [2]. However, there is no single, broad federal guideline to address exposure to indoor radon. Guidelines and recommendations for remedial action established by various agencies and organizations in the U.S. fall in the range of 4-8 pCi/l [9]. Lacking a single guideline, this range will be used as a broad indicator of the need for (and success of) mitigation activity.

One of the most widely tested source controls for radon is soil ventilation. Soil ventilation provides an alternative route of passage for radon gas -- into the outdoors instead of into a house (see Figure 1). This can be achieved by providing suction (and venting) of the air in the ground beneath foundation slabs, sump holes, drain tiles, or suction on the concrete block walls.

Increased house ventilation for radon mitigation is generally provided using air-to-air heat exchangers (AAHXs). In addition to their ability to provide increased ventilation, AAHXs transfer heat from the exhausted air stream into the supply stream, reducing the energy penalty associated with ventilation. House ventilation can also be provided by conventional fans blowing air through basements and crawl spaces. Additional detail on these and other controls for radon are discussed elsewhere [2, 10-15].

This analysis will provide a preliminary comparative assessment of the effectiveness of soil ventilation and house ventilation for a broad range of initial indoor radon concentrations, based on results reported to date. The aim of this work is to identify, if possible, a threshold of initial radon concentrations above which increased ventilation is unlikely to result in acceptable post-mitigation concentrations.

METHODOLOGY

The radon mitigation efforts to be summarized here include work by Advanced Technology Consultants, Ltd. in Canada [10], Turk et al in Spokane [11], Henschel and Scott in the Reading Prong, PA [12], Wellford in the Reading Prong [13], Sachs and Hernandez in NJ [14], and Nitschke et al in New York [15].

Before and after measurements for a total of 46 locations were used for the soil venting analysis, with 59 locations for house ventilation. (A "location" is a basement or a floor in the living area of a house; measurements in crawl spaces were not used.) Only locations with pre-mitigation radon levels in excess of 4 pCi/l were included. Data for more than one location in a single house has been

used in several cases. Also, more than one type of control has been applied to some houses, but in each case, the data used reflect the impact of each approach independent of the other [16].

This analysis includes applications of several different soil ventilation techniques. The data for house ventilation includes mechanical ventilation (with or without heat recovery) of the living area, basement and/or crawl space. Foundation crack-filling and sealing is an important component of both control approaches and often accompanied the soil venting and house venting efforts.

The data in this analysis are also qualified to some extent by limitations set by the author:

- More than one post-mitigation measurement in a specific location was used in cases where additional controls were utilized. For example, Turk [11] tested soil venting using both soil depressurization and overpressurization; both values have been used. The effect of this double-counting is to average an initial suboptimal result with a final success.

- One outright failure has been omitted from this analysis. Henschel and Scott [12] present one house in which a sub-slab venting system failed to reduce indoor radon below its initial value of 1240 pCi/l due to the lack of aggregate stone beneath the slab.

- Because radon entry is so strongly influenced by the stack effect [4], an effort was made to use before and after measurements reflecting similar seasons if data for more than one season was available.

- No adjustments are made for quantitative differences in individual house tightness, the amount of ventilation provided by the mechanical ventilators, nor have adjustments been made for other variables that may affect the success of a control such as soil porosity. These limitations will be discussed further following the presentation of results.

Some of the studies reported on here describe their data in radon progeny (working levels). These measurements are converted into the units of radon gas (pCi/l) for consistency [17].

RESULTS

The data have been binned according to pre-mitigation radon levels. Table I summarizes the results by mitigation technique. The average pre-mitigation concentrations within each bin are nearly equal between the two sets of data, suggesting the sets within each bin are comparable for the sake of this analysis. Also, the geometric and arithmetic means within each bin are nearly equal, indicating that the

binning ranges were appropriate for a lognormal distribution. The open-ended bins (> 80 pCi/l) are the exception, as expected for a lognormal distribution.

It is clear that both soil ventilation and house ventilation are successful mitigation techniques when initial concentrations are below 10 pCi/l. Both techniques reduced average radon concentrations below 2 pCi/l, and radon was reduced below 4 pCi/l in all but one individual location (a basement with mechanical ventilation).

The efficacy of soil ventilation continues into the bin where initial levels are 10 - 19.9 pCi/l, while the effectiveness of house ventilation declines in this range. The average level of radon after soil venting in these ten locations was again below 2 pCi/l, and all locations were reduced below 4 pCi/l. The average concentration after house ventilation was above 4 pCi/l, and post-mitigation levels exceeded 4 pCi/l in 7 of the 16 locations.

Soil ventilation is more effective at initial levels between 20 - 40 pCi/l. House ventilation reduced radon below 4 pCi/l in only one of 7 locations (with only two of 7 reduced below 8 pCi/l), while soil venting reduced two of 6 locations below 4 pCi/l (with 4 of 6 below 8 pCi/l).

Soil ventilation is clearly superior to house ventilation when initial radon levels are in excess of 40 pCi/l. Seven of the 15 post-mitigation measurements in houses with soil venting were at or below 4 pCi/l, compared to only 1 of 15 with house ventilation.

These results are also summarized in Figure 2, which shows the distribution of all the radon measurements before and after mitigation. The similarity of the two sets of data prior to the application of controls can be seen by the upper lines. The distribution of indoor concentrations after the use of the control measures are distinctly different. The estimated national distribution of radon in housing is also shown for comparison.

DISCUSSION

This compilation and analysis shows that a source control -- soil ventilation -- consistently reduces indoor radon concentrations to below 4 pCi/l when initial concentrations are up to 20 pCi/l, and soil venting is capable of reducing radon below 8 pCi/l in many cases regardless of initial indoor levels. In contrast, house ventilation is successful at reducing indoor radon concentrations below 4 pCi/l when initial levels do not exceed 10 pCi/l. These results confirm that source-specific controls for radon are more effective than dilution of the contaminated space.

There are other considerations that indicate controlling radon

at the source is the preferred approach. Table II compares the capital and operating costs of soil ventilation and house ventilation for control of radon. In addition to its superior performance, soil venting is less expensive than ventilation of the living areas.

Furthermore, mechanical ventilators are prone to interruption by occupants. One of the most common complaints concerning large mechanical ventilators (in general) is the noise they generate. Residents frequently shut them off in spite of their purpose [18]. The fans used to power soil ventilation systems are much smaller (hence quieter) than those used in house ventilators, and are always located in the basement or outdoors.

While this analysis provides a useful confirmation of the principle of radon source control, the quantitative results given here should be considered preliminary. Some of the data presented here are from the early stages of radon control research at particular sites. Individual house characteristics have not been considered, and other generalizations have been made for the purpose of comparing the principles of each application.

The main objective of the research efforts included in this paper has been the identification of reliable, low-cost mitigation techniques. The success of these efforts have been achieved in large part by the skill of the trained researchers and technicians involved in the work. More more research will be necessary before these and other radon control techniques become "off-the-shelf" practices for widespread applications. A growing number of remedial demonstration projects are in the planning stages in several states to help transfer these practices interested parties.

Who will complete the mitigation work necessary in the thousands of houses with unacceptable levels of radon? The transfer of these skills to contractors interested in pursuing radon mitigation as a source of income has not been widely discussed -- but it seems time to do so. How can quality control be assured? The mysterious nature of radon -- undetectable by the human senses -- presents many opportunities for "snake-oil salesmen" to exploit the demand for radon measurement and control [19].

Certification of qualified individuals and firms at the state level is appropriate for this technical work. The current asbestos abatement program administered by the states and guided by the EPA may serve as a useful model for a national radon mitigation effort. There are many commercial firms in the business of identifying and controlling environmental and occupational air quality problems. Many of these may soon add mitigation of radon and other indoor air pollutants to their repertoire. Certification will help maintain quality control and ensure sound business practices.

Energy auditors and retrofitters ("house doctors") may also find

providing air quality remedial services to be in their interest. Experienced house doctors are familiar with housing from basements to attics and they have hands-on experience with analytical equipment. Most importantly, house doctors understand houses as systems, and they work to improve occupant comfort as well as housing energy performance.

With additional training, some house doctors may choose to become "indoor air quality specialists". An initial house doctor visit may include both energy and air quality audits. The traditional house doctor would then improve the energy performance of the structure and refer the homeowner to a specialist if air quality problems are identified. In fact, one house doctoring firm has already established a subsidiary business to handle residential indoor air quality concerns, and two suppliers of home energy diagnostic equipment have added air quality monitoring and control equipment to their marketing efforts [20].

CONCLUSIONS

Indoor air pollution is not a problem for energy-efficient housing. The strength of a pollutant source is the primary determinant of the resulting indoor concentration of that pollutant. Residential construction with attention to pollutant sources can result in superior air quality in energy-efficient housing than in leakier homes where pollutant sources have not been addressed.

Efforts to control indoor air pollution in existing houses fall into two general categories: increased ventilation to dilute the indoor contaminants, and source-specific controls to limit the entry of pollutants into the house in the first place. Since the strength of a pollutant source is the main factor affecting its indoor concentration, it seems likely a source-specific control would be more effective at reducing indoor concentrations than an increase in ventilation.

This paper compared the effectiveness of two general control strategies for indoor radon: soil ventilation and house ventilation. Soil ventilation prevents radon entry into the living area by providing an alternative route of passage for radon gas. House ventilation reduces personal exposure to radon by diluting its indoor concentration through increased air exchange. Data from six recent field experiments across North America were used for this analysis.

The source control approach, soil ventilation, was found to be much more effective than general house ventilation. Soil ventilation is highly successful at reducing indoor levels below 4 pCi/l when pre-mitigation levels do not exceed 20 pCi/l, and soil ventilation often reduces radon below 8 pCi/l regardless of the initial concentration. Ventilation of the house volume is successful at reducing indoor radon below 4 pCi/l when pre-mitigation

concentrations do not exceed 10 pCi/l. House ventilation is generally unable to reduce radon below 8 pCi/l when pre-mitigation concentrations are above 20 pCi/l.

The source control approach for radon also appears preferable to general ventilation in terms of cost and the role of occupants. The capital costs of soil and house ventilation systems are roughly equal, but the annual operating costs of house ventilation are higher due to the more powerful fans and large volume of air moved by house ventilation. Also, general house ventilation can be shut down by occupants for a variety of reasons -- none of which are likely with soil ventilation.

However, a considerable amount of research remains necessary before these and other source-specific controls will be available for reliable, widespread applications. The data presented here were obtained from efforts by highly-skilled researchers and technicians. Additional applications and remedial demonstration efforts are needed to adequately train other potential field personnel.

Professional training and certification in radon mitigation is recommended at the state level to ensure that the public is protected from fraud and shoddy workmanship. There are many firms that already provide environmental and occupational air quality diagnostic and control services; these may find that radon in housing provides a new, profitable market.

"House doctors" may also find radon mitigation to be a logical extension of their current work on the energy performance of buildings. To this end, some house doctors may become "air quality specialists". Addressing indoor air quality is consistent with the purpose of house doctoring, that is, to improve the comfort and energy performance of housing. House doctors understand houses as systems and their dynamics -- skills sure to be useful in air quality remedial work.

REFERENCES AND NOTES

1. Of the dozens of articles concerning IAQ that this author has read in the popular press, only two media sources have not implicated energy conservation in the text of their articles: The New York Times and The Washington Post.

2. Morrill, J., Residential Indoor Air Quality and Energy Efficiency, American Council for an Energy-Efficient Economy, Washington, DC, forthcoming.

3. For example, two lighted cigarettes in a small room will produce over 100 times more respirable particles in an hour than the amount brought in with the outdoor air at 0.5 ACH. Additional examples are provided in reference 2.

4. Formaldehyde emissions from pressed wood products (and other major sources) can actually increase with increasing air exchange because of a vapor pressure effect (see Matthews, T.G., et al, "Formaldehyde Emissions from Combustion Sources and Solid Formaldehyde Resin Containing Products: Potential Impact on Indoor Formaldehyde Concentrations and Possible Corrective Measures", Proceedings of an Engineering Foundation Conference on Managements of Atmospheres in Tightly Enclosed Spaces, ASHRAE, 1983). Also, radon entry into housing is driven largely by the "stack effect" -- one of the processes that drives natural infiltration. Thus radon entry in the winter increases with increasing infiltration (see Nazaroff, W.W. et al, "Radon transport into a detached one-story house with a basement", Atmospheric Environment, 19:1, pp. 31-46, 1985.)

5. Sachs and Hernandez (reference 14) suggest ventilation may be sufficient for radon up to 20 pCi/l; Brennen and Turner suggest up to about 15 pCi/l (see "Defeating Radon", Solar Age, pp. 33-37, March 1986).

6. Radon also occurs in significant levels in well water in some locations. Rock-based building materials containing with appreciable radium content may also emit significant quantities of radon, however, the soil is the predominant source in most locations. See: Nero, A.V., "Airborne Radionuclides and Radiation in Buildings: A Review", Health Physics, 45:2, p. 303, August 1983.

7. Nero, A.V., et al, "Distribution of Airborne ^{222}Radon Concentrations in U.S. Homes", LBL-18274/EEB-Vent 84-33, Lawrence Berkeley Laboratory, Berkeley CA, November 1984.

8. "Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States", National Council on Radiation Protection and Measurements, NCRP Report No. 78, Bethesda, MD, May 1984.

9. The EPA established a guideline of 4 pCi/l for remedial work in housing contaminated with radon from the use of uranium mill tailings as backfill. The Bonneville Power Administration has established a guideline of 5 pCi/l for remedial efforts in its service area, and the NCRP (ref. 8) recommends remedial action at 8 pCi/l.

10. Advanced Technology Consultants (ATCON), Ltd., Investigation and Implementation of Remedial Measures for Radiation Reduction and Radioactive Decontamination of Elliot Lake Ontario, DSMA ATCON to the Atomic Energy Control Board (Canada), February 1981.

11. Turk, B.H. et al, "Radon and Remedial Action in Spokane River Valley Residences", LBL/EEB Vent 86-43.2 (draft report), 1986.

12. Henschel, D.B. and A.G. Scott, "The EPA Program to Demonstrate Mitigation Measures for Indoor Radon: Initial Results", International Specialty Conference on Indoor Radon, Air Pollution Control Association, Philadelphia, Feb. 1986.

13. Wellford, B.W., "Mitigation of Indoor Radon Using Balanced Mechanical Ventilation", presented at International Specialty Conference, op cit. (at ref. 12).

14. Sachs, H.M. and T.L. Hernandez, "Residential Radon Control by Subslab Ventilation", 77th Annual Meeting, Air Pollution Control Association, San Francisco, June 1984.

15. Nitschke, I.A. et al, "Indoor Air Quality, Infiltration and Ventilation in Residential Buildings -- Final Report", W.S. Fleming and Associates for New York State Energy Research and Development Authority, NYSERDA Report 85-10, Albany, March 1985.

16. One of the houses equipped with an AAHX by Wellford [13] had previously had a soil ventilation system installed. The original indoor concentration (prior to any remedial work) is unknown, and only the work performed by Wellford is included in this analysis. Turk et al [11] sealed and vented the crawl space of one house, reducing radon in the living area from 49.4 pCi/l to 19.9 pCi/l. A soil venting system was then installed, producing a further reduction to 3.3 pCi/l. Both of these results by Turk are included in this analysis.

17. Mitigation results were expressed in radon progeny (WL) by Advanced Technology Consultants, Henschel and Scott, and Wellford. Henschel and Scott actually measured radon gas and converted to WL for their report, using an equilibrium factor of 0.5; this factor was used to reverse the conversion. Wellford measured both radon gas and progeny; the equilibrium factors found in that work were used to convert from WL to pCi/l when pCi/l were not directly given. An equilibrium factor of 0.5 was used to convert the data reported by ATCON to pCi/l.

18. Lubliner, M. et al, "Experience With Air-to-air Heat Exchangers in the Residential Standards Demonstration Program in Washington State", this proceedings.

19. There is a substantial risk of fraud in both measurement and control of radon. According to an EPA official working on radon in the Eastern Pennsylvania area, some residents there have fallen victim to an individual who collects money for taking "air samples" in a mayonnaise jar. Also, the individuals who had solar panels installed facing north in the 1970's typify the public's vulnerability to unfamiliar devices.

20. The Princeton Energy Partners house doctoring firm has developed a subsidiary firm, Air Quality Control, to mitigate radon and other air quality concerns. Infiltec, Inc. in Virginia offers radon monitoring equipment and referral services. Retrotec, Inc. of Indianapolis, another major supplier of equipment to house doctors, is now marketing air quality monitors, vents, and air cleaning devices to its clientele.

21. Ericson, S.O., "Cost-benefit analysis of decreased ventilation rates and radon exhalation from building materials", p. 275, Indoor Air (Volume 5), Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, Stockholm, August 1984.

Table I. Effectiveness of Radon Control Techniques

Range of Initial Radon Level (pCi/l)	Number of Locations	Mean Radon Concentrations (pCi/l) - Before Control - GM	AM	Std.	- After Control - GM	AM	Std.
Soil Venting							
4.0 - 9.9	16	6.1	6.2	1.5	1.2	1.7	1.2
10.0 - 19.9	10	14.9	15.1	3.0	1.5	1.8	1.1
20.0 - 39.9	5	26.4	26.7	4.6	3.8	5.2	3.3
40.0 - 79.9	8	52.2	53.2	11.0	5.4	8.1	8.3
> 80	7	249	357	399	4.4	7.4	9.5
House Ventilation							
4.0 - 9.9	18	6.3	6.7	1.9	1.4	1.7	1.1
10.0 - 19.9	16	14.5	14.8	3.1	4.1	5.7	5.8
20.0 - 39.9	10	27.6	28.4	7.5	7.5	9.7	7.6
40.0 - 79.9	7	51.5	51.6	3.4	12.7	16.2	11.2
> 80	8	191	225	148	16.0	22.3	19.2

GM: geometric mean (median)
AM: arithmetic mean (average)
Std.: arithmetic standard deviation

Table II. Actual and Estimated Costs of Radon Mitigation

Reference	Installed Cost Range (average)	Annual Operating Cost
Soil Ventilation		
NYSERDA (5 houses) [15]	$146 - 1245 ($746)	n/a
Sachs and Hernandez [14]	200 - 1000	$40
Erickson [21]	650 - 1300	n/a
House Ventilation		
NYSERDA (4 houses) [15]	$777 - 1161 ($986)	n/a
Wellford [13]	800 - 1100	$175 - 274
Sachs and Hernandez [14]	500 - 1000	200 - 300

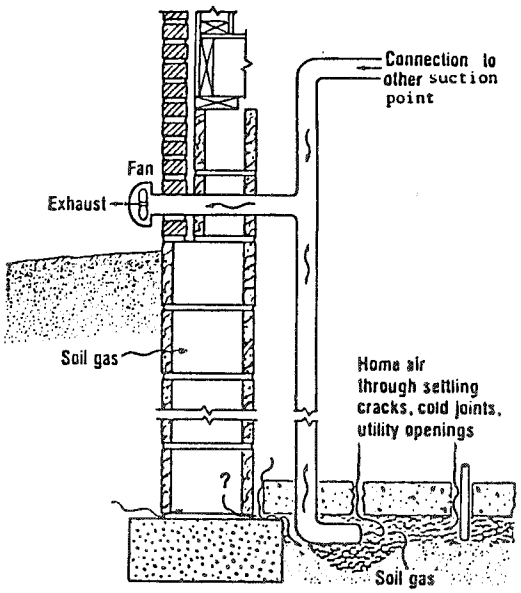

Figure 1. Example of a soil (sub-foundation) ventilation system. Reference 12.

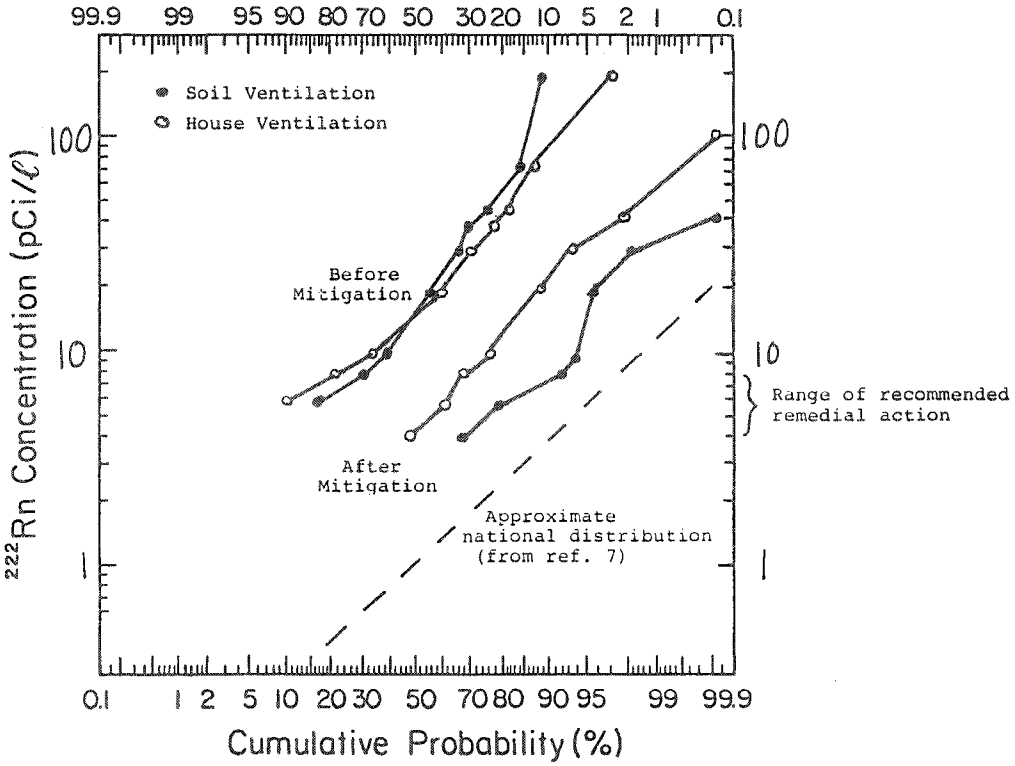

Figure 2. The distribution of indoor radon concentrations before and after mitigation. The shift in distribution of houses with soil ventilation is significantly greater than that for house ventilation.