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Project Summary

Evaluation of Waterborne Radon Impact on Indoor Air Quality and Assessment of Control Options

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This research program had two objectives: (1) evaluation of waterborne radon impacts on indoor air quality, and (2) assessment of available control technologies to limit indoor exposures to radon and its decay products.

The report reviews radon's physical, chemical, and radiological properties; summarizes its decay chain; and gives a synopsis of health risks, existing regulations, and recommendations concerning exposure to radon and progeny. Although the report is primarily concerned with air concentrations of radon and progeny resulting from waterborne sources, other potential sources (home subsurface, construction materials, fuel, and ambient air) and their potential impacts on indoor air quality are also discussed.

The report is the result of a literature search to identify and summarize research by investigators in the U.S. and abroad concerning the concentration of waterborne radon (C_w) and its effect on the indoor air concentration of radon (C_a). Major factors that influence C_a/C_w (including ventilation rate, water transfer efficiency, water use rates, and volume of the home) are examined. Sensitivity analyses are conducted to mathematically define a representative value for C_a/C_w (0.7×10^{-4}) and its reasonable bounds (0.17×10^{-4} to 3.5×10^{-4}).

The report also assesses reported techniques for removing radon from water or indoor air. Techniques evaluated for removing radon from water include decay, aeration, and granular activated carbon. Techniques evaluated for removing radon and/or progeny from air include circulation, ventilation, filtration, electrostatic precipitation, charcoal adsorption, chemical reaction, and space charging. Where the reports examined include a sufficient amount of information to do so, an evaluation of the cost, efficiency, and practicality of each technique is provided.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Radon 222 (^{222}Rn) is a naturally occurring radioactive gas produced by the decay of radium in the uranium decay series. ^{222}Rn undergoes radioactive decay by emission of alpha particles with a characteristic half-life of 3.82 days. ^{222}Rn decay products include a series of short half-life (30 minutes or shorter) radioactive isotopes commonly referred to as radon "daughters" or radon "progeny." All progeny are solid particles and are chemically active metals, including ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po.

Exposure to ^{222}Rn and radon progeny present in indoor air can occur from various sources. Primary sources of ^{222}Rn in buildings are the soil adjacent to the foundation, construction materials, and potable water supplies. Background ^{222}Rn in ambient air and presence in home heating fuels are normally of lesser importance. This report is concerned primarily with waterborne sources of ^{222}Rn, and their impacts on the indoor-air quality of homes.

Small quantities of ^{222}Rn can be found in all groundwater from natural sources as a result of decay of radium in water and diffusion from the rock and soil matrix surrounding the water. Many investigators have quantified concentrations of ^{222}Rn in water supplies. In the U.S., typical ^{222}Rn levels in potable water generally fall below 2,000 pCi/l, but concentrations exceeding 300,000 pCi/l have been noted. Specific areas with high concentrations include portions of Maine, New Hampshire, North Carolina, Texas, Arkansas, Florida, and Utah.

Health risks due to exposure to ^{222}Rn and radon progeny are mainly due to the emission of alpha particles from ^{218}Po and ^{214}Po. Exposure of body tissues to radioactivity entering the home in waterborne ^{222}Rn can occur through both ingestion of water and inhalation of ^{222}Rn decay products. Early studies focused on ingestion as the most important exposure from an epidemiological viewpoint. However, recent studies suggest that the dose to the lung is the limiting factor in determining the maximum permissible concentration of ^{222}Rn in water

Because of the importance of the inhalation pathway, many investigators have recently attempted to correlate ^{222}Rn concentrations in water supplies (C_w) with resulting concentrations in the air of typical homes (C_a). Once defined, this air-to-water concentration ratio (C_a/C_w) can be used to assess health risks associated with ^{222}Rn concentrations in water supplies.

This assessment of a representative C_aC_w for homes involves many considerations. The quantities of ^{222}Rn released into a home depend on transfer efficiencies associated with each type of use (which range from <10 to >98%) as well as the quantities of water used. Once released, ^{222}Rn begins to decay to its progeny, and the concentrations of ^{222}Rn and progeny in the home at any time depend on the volume of the home and its ventilation rate.

Exposures to ^{222}Rn and its progeny can be controlled either by removing ^{222}Rn from water supplies, or by removing ^{222}Rn and/or its progeny from air. Several techniques are available.

Survey of Existing Information

The initial phase of this project included a summary of the general concepts and properties of ^{222}Rn. Information presented includes the physical and chemical properties of ^{222}Rn; explanations of ^{222}Rn decay, progeny, and associated health effects; a synopsis of federal regulations on ^{222}Rn; and presentation of the sources and source strengths of ^{222}Rn entering homes. Figure 1 shows the radioactive decay chains for ^{238}U and ^{222}Rn. Table 1 summarizes source contributions to the indoor ^{222}Rn concentration

Waterborne Radon and Effects on Indoor Air Quality

An analysis is made of the factors that affect the transfer of ^{222}Rn from potable water supplies to the indoor air, and (once in the air) the factors that affect its concentration. Major items discussed include the water-to-air transfer efficiencies, factors that affect the indoor ^{222}Rn air level, a review of previous studies relating the potable water ^{222}Rn level and that in household air, and the development of a mathematical relationship between the potable water ^{222}Rn level and that in household air

The transfer of a gas such as ^{222}Rn from a region of higher concentration (potable water) to that of a lower concentration (household air) is referred to as mass transfer. Mass can be transferred by random molecular motion in quiescent fluids (molecular mass transfer) or by transfer from a surface into a moving fluid, aided by the dynamic characteristics of the flow (convective mass transfer). These two phenomena control the rate at which ^{222}Rn can be out-gassed through water use in typical household activities. Major household activities that transfer ^{222}Rn to the indoor air, along with typical transfer efficiencies, are shown in Table 2.

Major factors which affect the ^{222}Rn mass transfer include: (1) increasing the area of the water-to-air interface (e.g., by using a spray) increases the mass transfer across the boundary layer and (thus) increases the transfer efficiency, and (2) increasing the water temperature results in greater ^{222}Rn transfer efficiency.

Major factors found to affect the indoor ^{222}Rn air level (assuming the transfer of ^{222}Rn from potable water is the only source of interest) include the concentration of ^{222}Rn in the potable water, the average transfer efficiency of ^{222}Rn from water to air, the types and volumes of household water use, the ventilation rate of the house, and the volume of the house. Based on a thorough review o literature, the following values were assumed typical for four of these major parameters:

f = 0.55 (transfer efficiency of radon from water to air),
λ = 1.0 hr^{-1} (ventilation rate in air changes per hour),
V_{house} = 75,000 liters/person (volume of house which is equal to the volume of an air change), and
V_w = 9.5 liters/hr/person (household water use).

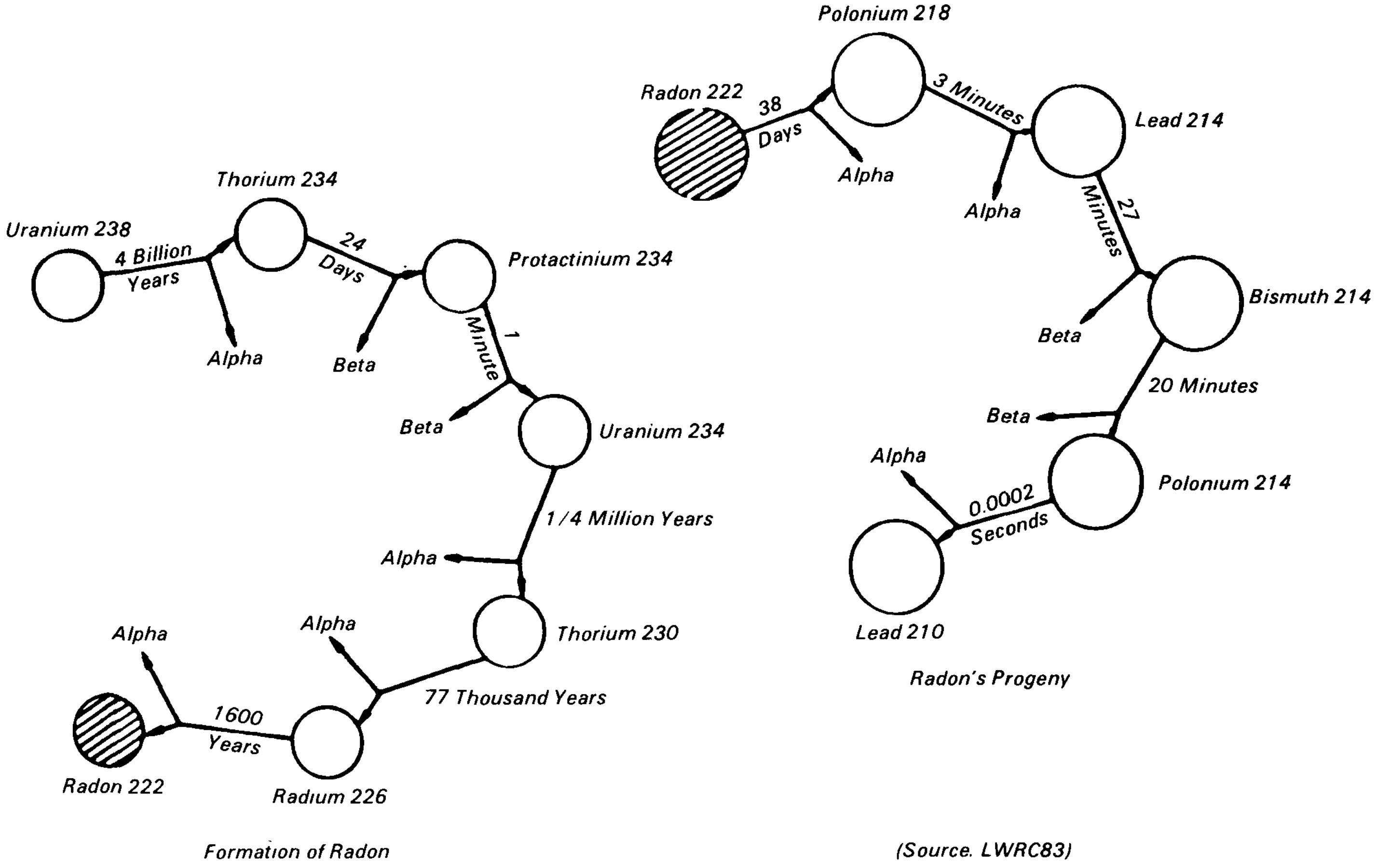
Available literature data relating potable water ^{222}Rn concentration (C_w) to ^{222}Rn concentration in the household air (C_a) are summarized in Table 3, along with major experimental conditions or assumptions. A thorough review of each literature source is contained in the report.

A mathematical relationship between the potable water ^{222}Rn concentration and resulting concentration in the household air was developed. The steady-state equation relating the air/water concentration ratio to four other major variables is.

$$C_a/C_w = \frac{(f)(V_w)}{(\lambda)(V_{house})} \qquad (1)$$

where
C_a = Concentration of ^{222}Rn in air (pCi/l),
C_w = Concentration of ^{222}Rn in water (pCi/l),
f = Transfer efficiency of ^{222}Rn from water to air,
V_w = Household water usage (liters/hr),
λ = Ventilation rate in air changes per hour (hr^{-1}), and
V_{house} = Volume of the house which is equal to the volume of an air change (liters).

Table 4 presents typical, maximum, and minimum reasonable values for each variable. These variables are then ar



Formation of Radon

Radon's Progeny

(Source. LWRC83)

Figure 1. Radioactive decay chains for uranium and radon.

Table 1. Summary of Source Contributions to the Indoor Radon Air Concentration[a]

Source	Calculated in this Report pCi/l	Br83 pCi/l
Soil, Rock, Home Subsurface	0.01 - 2.7	0.05 - 2.4
Building Materials	0.02 - 0.7	0.005 - 0.5
Potable Water	0.1 - 13.6	0.2 - 28
Home Heating Fuels	0 003 - 0 0016	-
Ambient Air	0.0001 - 3.5	-

[a] Basis: House volume = 230,000 liters.
Ventilation rate = 1 air change per hour.

ranged in Equation (1) to generate the minimum, typical, and maximum values of the ratio C_a/C_w, as shown in Table 5. These tables show that, under typical conditions, the ratio C_a/C_w closely approximates the "10^{-4}" empirical value and for our assumptions is 0.7×10^{-4}. Conditions that generate a minimum value for the ratio C_a/C_w are called "conservative," and those that generate a maximum value are called "liberal" conditions.

Limited data are available in the literature that relate a measured C_a/C_w ratio to the other major variables. Actual monitoring data are summarized in Table 6 and graphically displayed in Figures 2 through 4. These figures, which also list the boundary conditions established by the assumptions listed in Table 5, show that actual data closely approximate the typical assumption plot that almost all data fall within the boundary conditions established by the liberal and conservative assumptions.

Thus, although one empirical number cannot be selected as the water/air diffusion factor, a range of numbers can be defined based on reasonable boundary conditions. This range has been shown to vary from 0.17×10^{-4} to 3.48×10^{-4} under typical conditions.

Control Technology Evaluations

The report discusses the applicability of the various control technologies that are available for removing ^{222}Rn from water sources and also for controlling airborne concentrations of ^{222}Rn and its progeny after entering the home. An evaluation is made of the cost, efficiency, and applicability of each control technology where sufficient information is available.

Table 2. *Measured ^{222}Rn Water/Air Transfer Efficiencies for Typical Household Activities*

Activity	Transfer Efficiency (% ^{222}Rn Released) EPA77	Pa79	Ge80	He81	He82
Laundry Washing:					
Hot wash cycle (18 min) with soap		98 4±1.3			
Hot wash cycle (13 min) without soap		97.9±2.7			
Cold wash cycle (18 min) with soap		93 3±5.2			
Cold wash cycle (18 min) without soap		93 5±3.4			
Warm wash cycle (18 min) with soap		98.3			
Cold wash cycle (11 min) with soap		91.4			
Cold wash cycle (4 min) with soap		84.7			
Cold wash gentle-cycle with soap		78.7			
Cold wash gentle-cycle without soap		76 6			
Cold rinse regular cycle		80.9±17 4			
Cold rinse gentle cycle		62.2			
No specific description given			90[a]	90[a]	90[a]
Dishwasher.					
Wash Cycle		97.7±3 7			
Rinse cycle		98.5±2.1			
No specific description given			98	98	98
Bath Tub.					
Hot water		59.7			
Warm water		36.2			
Cold water		37.8			
No specific description given			47	30[a]	30[a]
Shower					
Warm water		71.2±4.7			
No specific description given	91		63	65	65
Sink					
Warm water		28.3			
No specific description given				30[a]	10-15[a]
Toilets					
Tank		4.9±11 3			
Bowl		23 6±6.5			
No specific description given			30	30[a]	30[a]
Drinking and Kitchen					
No specific description given			30		
Cleaning:					
No specific description given			90		
Overall Weighted Average for All Household Uses		62 5	52	59	59

[a] *Estimated*

Table 3. *Summary of C_a/C_w Literature Data*

Source	C_a *pCi/l*	C_w *pCi/l*	C_a/C_w *(x 10^{-4})*	*Experimental Conditions/Basis*	
UN77	0 2	1,000	1 0	*Series of assumptions: 4 people, water use = 1000 liters/day, 230,000 liters =* V_{house}, $\lambda = 1\ hr^{-1}$, $f = 1.0$.	
He78	0.09	100	9.0	λ *unknown, actual data based on measurements of Ca in the same room as the source. Led authors to conclude* $C_a/C_w = 10^{-4}$.	
	0.3	3,000	1.0		
	0.7	9,000	0.78		
	4.5	60,000	0.75		
	5.0	85,000	0.59		
	10 0	85,000	1 2		
He79	2.4±1.2	60,000	(0.4±0 2)	$\lambda = 3\ 0\ hr^{-1}$	*24 hr radon values in these dwellings. Wrenn-Spitz-Lundum measurements*
	2.6±0.7	1,480	(18±5)	$\lambda = 1\ 1\ hr^{-1}$	
	10.3±1.6	24,810	(4±2)	$\lambda = 1.0\ hr^{-1}$	
	3.9	87,430	0.45	$\lambda = 2.1\ hr^{-1}$	
	3.3	32,670	1.0	*school,* λ *= unknown*	
Pa79	0.18	10,000	0.18	$\lambda = 2\ 0\ hr^{-1}$	$V_w = 23.3$ *liters/hr* $f = 0.625$
	0.42	10,000	0.42	$\lambda = 1\ 0\ hr^{-1}$	

Removal of Radon from Water Sources

Major technology evaluated for ^{222}Rn removal from water sources in homes includes decay in a holding tank, aeration, and granular activated carbon. A detailed description of each technology is included in the report. Table 7 summarizes available information concerning the removal efficiencies, capital and operating costs, and practicality of each technique.

It was judged that decay is not practical for typical domestic situations due to the long holding time and large storage capacity required.

A comparison of aeration versus carbon adsorption for removing ^{222}Rn from potable water supplies, once the water has reached the residence, leads to the following conclusions.

1. ^{222}Rn removal using aeration is highly variable, and removal efficiencies are highly dependent on the system's ability to de-gas the ^{222}Rn once aeration has taken place.
2. Potable water in the home would have to be aerated in an isolated well-ventilated area to adequately disperse out-gassed ^{222}Rn outdoors.
3. The initial capital cost, operating cost, and maintenance of an aeration system would be higher than those of an activated carbon system because of the use of motors and compressors. The cost advantage of granular activated carbon versus aeration appears to hold true particularly for low to moderate influent ^{222}Rn concentrations (less than 50,000 pCi/l).
4. More consistent and higher removal efficiencies have been demonstrated for carbon adsorption. Literature sources indicate that 62 to 99.8 percent of ^{222}Rn can be removed from water by carbon adsorption.
5. The operation of a carbon adsorption unit is judged to be easier than that of an aeration system for domestic operations.

Control of Indoor Air Concentrations

Several treatment technologies can be used to reduce the level of ^{222}Rn and/or progeny in indoor air. Technologies evaluated include circulation, ventilation, filtration, charcoal adsorbers, chemical reaction, and space charging. Each tech-

Table 3. (*Continued*)

Source	C_a pCi/l	C_w pCi/l	C_a/C_w ($\times 10^{-4}$)	Experimental Conditions/Basis		
	0.78	10,000	0.78	$\lambda = 0.5\ hr^{-1}$	$V_{house} = 4x10^5$ liter	
	1.3	10,000	1.3	$\lambda = 0.25\ hr^{-1}$		
	0.92	10,000	0.92	$V_{house} = 1.4x10^5$	$V_w = 23.3$ liters/hr	
	0.40	10,000	0.40	$V_{house} = 3.4x10^5$	$f = 0.625$	
	0.18	10,000	0.18	$V_{house} = 6.6x10^5$	$\lambda = 1.0\ hr^{-1}$	
Ge80	1	10,000	1.0	Estimation Basis, V_{house} = 200,000 liters		
					V_{house} (liters)	(hr^{-1})
	0.51	1,000	5.1	Calculated	150,000	0.25
	0.11	1,000	1.1		340,000	0.50
	0.05	1,000	0.5		340,000	1.0
	0.01	1,000	0.1		680,000	2.0
	0.35	1,750	2.0	Actual Measurements	175,000	0.25
	0.04	700	0.57		340,000	1.0
	0.18	2,000	0.90		340,000	0.5
	0.10	2,000	0.5		500,000	1.0
Ka80 (Finland)	unknown		1.4	Housewives and small children		
	unknown		0.6	Other persons.		
	unknown		0.87	Population weighted coefficients for all of Finland.		
Mc80	0.5	158,000	0.032	Nova Scotia, Canada trailers, actual measurements		
	3.2	164,000	0.2			
	0.6	152,000	0.039			
	2.0	158,000	0.13			
	4.1	168,000	0.24			
	2.5	148,000	0.17	school		
	0.5		0.034			
	3.4	129,000	0.26	Conventional homes		
	2.2	43,000	0.51			
	0.7		0.16			
	1.2	98,000	0.12	School		
	0.6		0.061			
	19.1	370,000	0.52	Conventional homes		
	6.6		0.18			
	1.5	190,000	0.079			
	3.0		0.16			
	3.3	314,000	0.11			
	1.2		0.038			
NRC81	0.2	1,000	1.0	General statement		
He81			0.75±0.1	Average of 18 homes in Maine.		
	1.9	52,000	0.37	Normalized to $\lambda = 1\ hr^{-1}$, corrected Graphically: $(0.6 \pm 0.1) \times 10^{-4} = C_a/C_w$ Add 25% for weak sources $(0.75 \pm 0.1) \times 10^{-4} = C_a/C_w$		
	1.7	17,000	1.0			
	3.2	27,000	1.2			
	0.7	6,500	1.2			
	4.5	28,000	1.6			
	3.0	18,000	1.7			
	<0.3	330	9.1			
	<0.3	330	9.1			
	<0.3	330	9.1			
	1.5	22,000	0.68			
	1.5	25,000	0.60			
	1.0	8,000	0.13			
	5.0	28,000	0.18			
	<0.3	330	9.1			
	3.8	52,000	0.73			
	0.85	17,000	0.50			
	1.6	27,000	0.59			
	0.35	6,500	0.54			
	2.0	28,000	0.71			
	1.0	18,000	0.56			

nology is discussed in detail in the report. Table 8 summarizes available information on each treatment technology as it pertains to ^{222}Rn and/or progeny removal. Because the capital cost of household control equipment is highly dependent on existing heating, cooling, and duct work systems and associated ventilation rates, conclusions concerning the advantages of one system over another are highly site-specific.

Conclusions

1. Concentration of ^{222}Rn in water, at concentrations exceeding about 1000 pCi/l, have a measurable impact on indoor air quality.
2. C_a/C_w, the ratio of airborne ^{222}Rn resulting from water supplies to the waterborne concentration of ^{222}Rn, has been measured as low as 0.032×10^{-4} and as high as 59.0×10^{-4} in individual homes.
3. Most measurements and estimates of C_a/C_w reported in the literature range from about 0.18×10^{-4} to 2.0×10^{-4}.
4. The value of C_a/C_w in homes depends primarily on home ventilation rates; volume of the home; volumes, types, and diurnal variations in water use; and water-to-air transfer efficiency. In addition, measurement of C_a/C_w can be affected by the types and locations of ^{222}Rn monitoring equipment used, indoor humidity, meteorological conditions, circulation systems and architectural style of the home, experimental errors, and complications due to non-waterborne sources of ^{222}Rn entering the home.
5. The value of C_a/C_w as referred to in this report expresses a time- and volume-weighted average which could be used to develop relationships between cumulative exposure rates to residents of homes and resulting health effects. C_a/C_w does not evaluate short-term or site-specific acute exposures.
6. Work reported by Hess (He82), based on studies in 18 homes in Maine, provides measured values for C_a/C_w in experiments designed to eliminate some of the variation in C_a/C_w due to ventilation rates, non-waterborne sources, and monitoring location. The authors report $C_a/C_w = (0.8 \pm 0.2) \times 10^{-4}$ for C_a measured by Wrenn detectors in

Table 3. *(Continued)*

Source	C_a pCi/l	C_w pCi/l	C_a/C_w ($\times 10^{-4}$)	Experimental Conditions/Basis
He82			(0.8±0.2)	Normalized to $\lambda = 1\ hr^{-1}$, corrected radon bursts by 33% to account for radon from all water
UN82	--	--	1.5	$f = 1.00$ (NEA78)
	--	--	1.0	(Du76)
	229 (avg. 32 obs.)	138,000 (avg. 20 homes)	20.6	avg. C_a/C_w for 32 rooms, situations where much water used (showers).
	78 (avg. 47 obs.)	138,000	5.64	avg. C_a/C_w for 47 rooms, situations where little water used (cooking).
	5.92 (avg. 20 obs.)	138,000	0.60	avg. C_a/C_w for 20 living rooms, situations where no water used (An78).
He83			1.3	avg. C_a/C_w in 70 homes, discounting other sources (not normalized for λ).

Table 4. *Variable Ranges*

Parameter	Minimum Values	Typical Values	Maximum Values
f	0.25	0.55	1.0
V_w (liter/hr/person)	4.75	9.5	19
V_{house} (liters/person)	37,500	75,000	150,000
λ (air change/hr)	0.2	1.0	2.0

Table 5. *C_a/C_w Range*

Parameter	Conservative Variables that Generate Minimum C_a/C_w	Typical Variables	Liberal Variables that Generate Maximum C_a/C_w
f	0.25	0.55	1.0
V_w (liters/hr/person)	4.75	9.5	19
V_{house} (liters/person)	150,000	75,000	37,500
V_w/V_{house} (hr^{-1})	3.17×10^{-5}	1.27×10^{-4}	5.07×10^{-4}
λ (air change/hr)	2.0	1.0	0.2
C_a/C_w	3.96×10^{-6} or 0.0396×10^{-4}	6.97×10^{-5} or 0.697×10^{-4}	2.53×10^{-3} or 25.3×10^{-4}

the living room of homes, with ventilation rates standardized to 1.0 hr^{-1}. The authors also report $C_a/C_w = 1.3 \times 10^{-4}$ without standardizing for ventilation rate.

7. Sensitivity analyses completed for this report suggest that, when a typical range of values for ventilation rate, water-to-air transfer efficiency, and ratio of water use to home volume are assumed, C_a/C_w may be expected to have an average value of 0.7×10^{-4} and a range of 0.17×10^{-4} to 3.5×10^{-4}
8. The value of C_a/C_w is likely to vary diurnally over a range of approximately one order of magnitude in most domestic situations due primarily to sporadic water use, location of monitoring sites with respect of waterborne ^{222}Rn sources, and fluctuating ventilation rates.
9. Presence of radon progeny is more directly responsible for health effects than is ^{222}Rn gas. The concentration of radon progeny in air due to waterborne sources, measured in working levels, has not been investigated to the extent that C_a/C_w has.
10. ^{222}Rn can be removed from water by decay, aeration, or carbon adsorption. Efficiencies exceeding 90 percent have been reported to be achievable through each technique. Based on cost, efficiency, and practical operability, carbon adsorption appears to be the most advantageous choice for most domestic applications.
11. Removing ^{222}Rn and/or radon progeny from indoor air has been demonstrated by circulation, ventilation, filtration, electrostatic precipitation, and charcoal adsorption. Removal efficiencies of 50 - 95 percent have been reported. Removal efficiencies depend on ventilation rates, circulation systems, degree of plate-out occurring, humidity, particle size distribution, and other factors. Selection of control systems for individual homes, based on efficiency, cost, and practicality, is highly site-specific and would depend on the heating, cooling, and circulation systems already in place.

Recommendations

1. The value of C_a/C_w is based on theoretical calculations and/or measurements at relatively few homes. An expanded monitoring program, using standardized monitoring techniques in a cross-section of geographic areas of the U.S., may be desirable.
2. Further monitoring, if conducted, should be designed and implemented to reduce and quantify uncertainties in C_a/C_w which result from sampling procedures, monitoring locations, measurement of ventilation rates, circulation patterns in the home, meteorological influences, inadequate water use records, diurnal and seasonal variations, contributions from sources other than water, etc.
3. Further research in the relationships between the concentration of radon in water and resulting concentrations of progeny in air would provide valuable information

Table 6. *Actual Monitoring Data Illustrating the Relationship Between the Air-to-Water Concentration Ratio and Other Major Variables*

Source	No. of Occupants	λ hr^{-1}	f	V_w l/hr	V_{house} l	Actual C_a/C_w	Predicted (Eq. 1) C_a/C_w
Ge80	4	0.25	0.52	37.1	175,000	2.0×10^{-4}	4.4×10^{-4}
	4	1.0	0.52	37.1	340,000	0.57×10^{-4}	0.57×10^{-4}
	3	0.5	0.52	27.8	340,000	0.90×10^{-4}	0.85×10^{-4}
	5	1.0	0.52	46.4	500,000	0.50×10^{-4}	0.48×10^{-4}
He81	4	2.0				0.37×10^{-4}	
	3	0.5				1.0×10^{-4}	
	4	0.5				1.19×10^{-4}	
	2	0.5				1.08×10^{-4}	
	3	0.5				$<1.8 \times 10^{-4}$	
	2	0.4				1.61×10^{-4}	
	5	0.3				1.67×10^{-4}	
He83		1.0				0.8×10^{-4}	
He79		3.0				$(4 \pm 2) \times 10^{-5}$	
		1.1				$(1.8 \pm 0.5) \times 10^{-3}$	
		1.0				$(4.2 \pm 0.6) \times 10^{-4}$	
		2.1				4.5×10^{-5}	

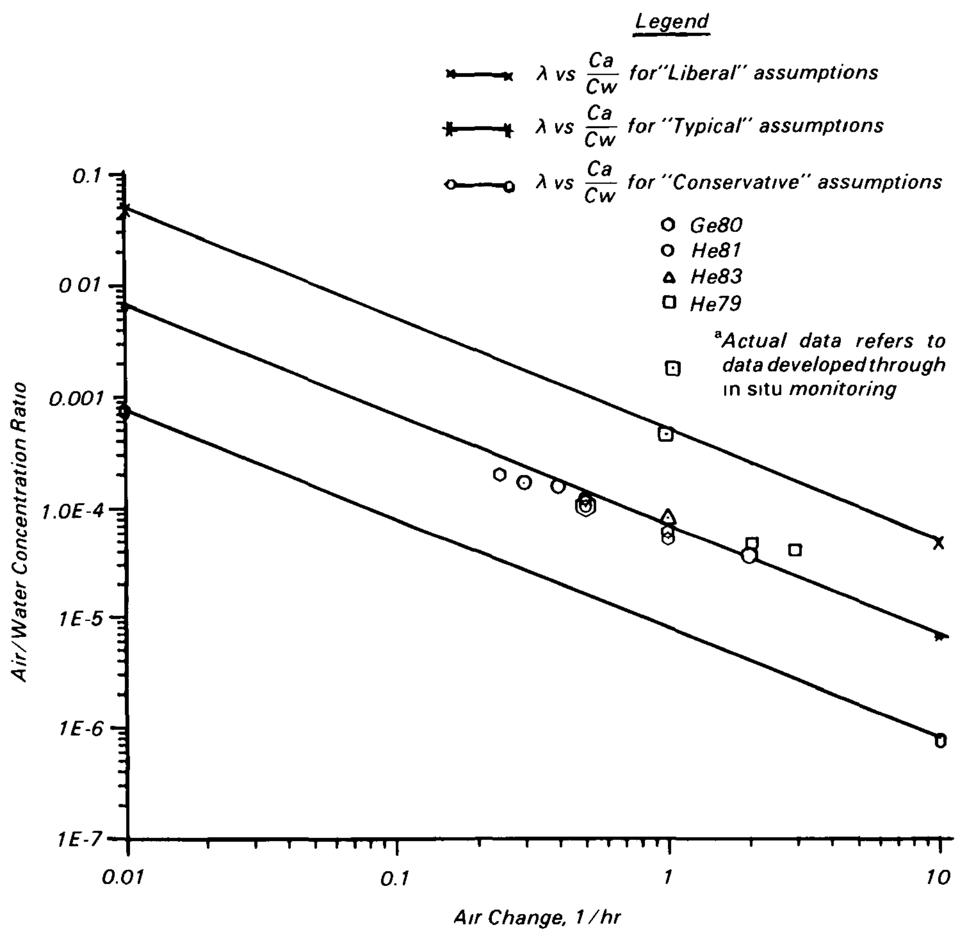


Figure 2. *Actual monitoring data[a] showing relationship between air/water concentration ratio and air change rate.*

4. Exposure to progeny during periods of close proximity to the waterborne source has not been fully evaluated.
5. The cost, efficiency, and practicality of various control technologies, particularly for removing ^{222}Rn and progeny from air, have not been firmly established.

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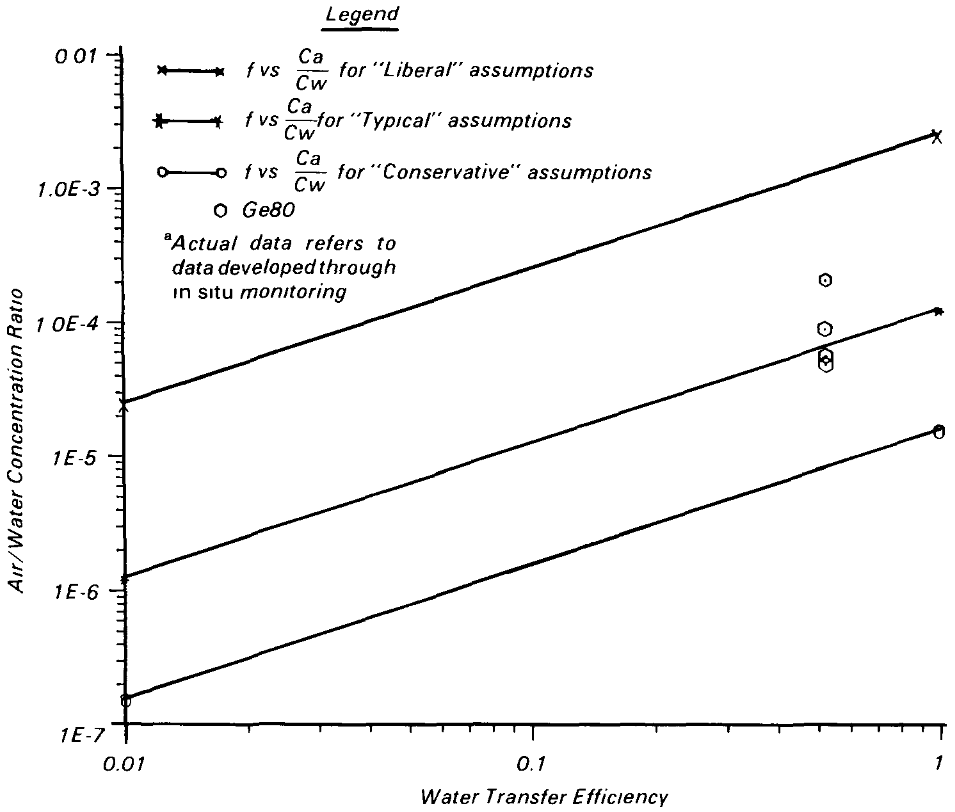

Figure 3. *Actual monitoring data[a] showing relationship between air/water concentration ratio and water transfer efficiency*

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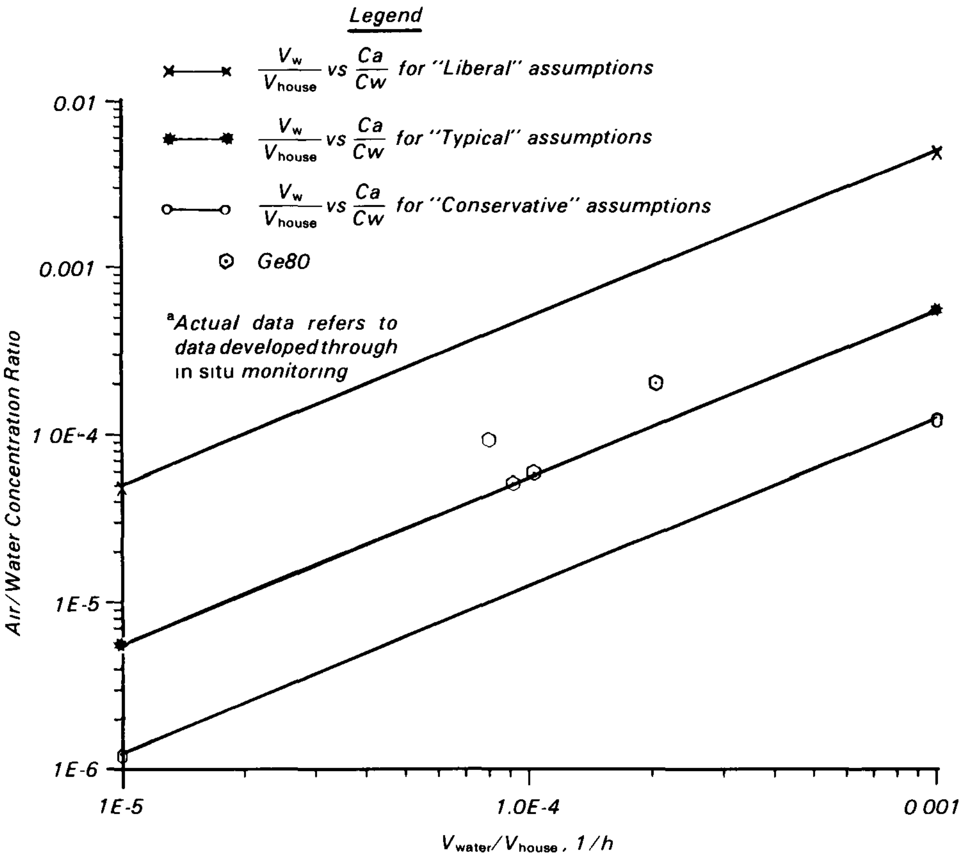

Figure 4. *Actual monitoring data[a] showing relationship between air/water concentration ratio and V_w/V_{house} ratio*

Table 7. *Summary of Techniques to Achieve Removal from Water at Homes*

Technology	Potential Removal Efficiency ^{222}Rn, %	Cost in 1983 Dollars Capital	Annual O&M	Comments
Decay in Holding Tank	Up to 96.9-99.6	NA[a]	NA	Judged impractical due to size requirements
Aeration	20-96	\$890-\$1000	\$60-\$80	
Granular Activated Carbon	62.1-99.8 92.5 avg.	\$431-\$1500	\$10-\$40	Cost dependent on influent concentration; judged easiest to operate

[a] NA = Not available

Table 8. *Summary of Techniques to Remove ^{222}Rn and Progeny from Air in Homes*

Technology	Potential Removal Efficiency, %		Costs in 1983 Dollars		Comments
	^{222}Rn	Rn Progeny	Capital	Annual O&M	
Circulation (fans)	0	50-63	20-150	--[a]	Assuming no ventilation rate change
Ventilation:					
Natural (open window)	94	91	0	0	Increases ventilation rate by factor of 11; neglects heat/cooling loss
Forced Air Heating & Cooling	79	91	0	0	Costs are routinely incurred
Central Fan (increase vent rate 3.7 times)	80	89	20-150	320	Annual costs for additional heating (only) based on doubling ventilation rates
Combined ESP/outside exchange system	0	62[b]	1400	165+	
Ventilation combined with air-to-air heat exchange	34-87	--	100-1400	25-250	Costs depend on ventilation rate achieved
Air Cleaner					
Filtration	0	<90	--	--	
Electrostatic Precipitator	0	73-95	--	--	
Charcoal Adsorber	--	--	--	--	
Chemical Reaction	99	--	--	--	Experimental
Space Charging	--	--	--	--	No information

[a] -- = insufficient data.

[b] Based on mathematical modeling

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The complete report, entitled "Evaluation of Waterborne Radon Impact on Indoor Air Quality and Assessment of Control Options," (Order No. PB 84-246 404; Cost: $14.50, subject to change) will be available only from:

National Technical Information Service
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