Paper

SPATIAL VARIATION OF WATERBORNE RADON AND TEMPORAL VARIATION OF RADON IN WATER AT NINE MAINE SCHOOLS

V. E. Guiseppe, T. J Gould, and C. T. Hess*

Abstract—**Nine elementary schools in Maine were examined to track the release of ^{222}Rn and to determine the transfer coefficient from water into air. Water-use simulations were performed by running sinks and sprayers for 1 h in a kitchen. The ^{222}Rn in air was measured over 24 h throughout the school. The subsequent release of ^{222}Rn into the kitchen air was measured to be greater than the EPA action level of 0.15 Bq L^{-1} (4 pCi L^{-1}), but negligible concentrations of ^{222}Rn were found in adjacent classrooms. In two schools, more than 10 ^{222}Rn-in-air detectors were placed throughout the kitchen and showed a three-fold spatial concentration variation. During the hour-long simulations, the ^{222}Rn in water concentration was measured periodically, and many of the schools showed an increase in the ^{222}Rn concentration in water before remaining constant. These measured variations suggest that multiple detectors are needed to accurately measure waterborne ^{222}Rn in air, and multiple delayed measurements of ^{222}Rn dissolved in water are needed to obtain a representative groundwater sample.**

Health Phys. 92(4):358–365; 2007

Key words: radon; groundwater; transfer coefficient; ventilation

INTRODUCTION

^{222}Rn is a naturally-occurring, inert radioactive gas formed in the ^{238}U decay series. ^{222}Rn is found in soils and rock where its radioactive parent ^{226}Ra and ^{238}U are found. According to the U.S. Environmental Protection Agency (EPA), ^{222}Rn is considered a carcinogen and is the second leading cause of lung cancer (U.S. EPA 1999). It can escape from the ground and build up in low concentrations in outside air and accumulate in basements and homes (Eisenbud and Gesell 1997). The EPA has set an action level of 0.15 Bq L^{-1} (4 pCi L^{-1}) for indoor ^{222}Rn concentrations. Since ^{222}Rn can dissolve and remain in groundwater until dispensed and aerated, kitchen and bathroom appliances provide an additional pathway of ^{222}Rn into a building. The EPA has proposed setting maximum contaminant levels for ^{222}Rn in groundwater. The standard will be based on the fraction of ^{222}Rn that escapes the water during use (U.S. EPA 1999), which is defined as the ^{222}Rn transfer coefficient.

Previous studies have measured the average ^{222}Rn transfer coefficient to be between 1×10^{-5}–5×10^{-4} in homes (Duncan et al. 1977; Prichard and Gesell 1981; Hess et al. 1982; Lachapelle 1988). An investigation identified ^{222}Rn transfer coefficients at rural schools in Maine that draw water from private wells (Norris et al. 2004). Schools were a logical progression from homes due to the large amounts of water used during the day and long exposure time for occupants. A model was used to calculate a transfer coefficient for the school kitchen and compared against the measured change in the ^{222}Rn concentration while using water. The measurements of released ^{222}Rn did not agree within experimental uncertainty to those predicted by the model. At one school, four detectors were placed in a kitchen and a decrease of ^{222}Rn with distance from the water faucet was observed. Norris et al. (2004) suggested that a variation of radon throughout the room could cause the discrepancy between the modeling and measurement of transfer coefficients.

Researchers have observed temporal variations of ^{222}Rn in water to be dependant on water usage history and purging effects (Hightower and Watson 1995). Nine sites in North Carolina were sampled monthly and the data suggested that sites with well pumps running during the measurements or recently running showed the least variation. At one location, purging the water for 140 min for three of the sampling runs was sufficient to obtain consistent ^{222}Rn concentrations. During three successive monthly sampling runs, they measured the ^{222}Rn concentration every 10 min and found a significant increase during the first 60 min with a slight decrease over the remaining 80 min. At one of the locations, one sampling run was done after days of vacancy and consequently no

* The University of Maine, Department of Physics and Astronomy, 5709 Bennett Hall, Orono, ME 04469-5709.

For correspondence contact V. E. Guiseppe at the above address, or email at vguiseppe@gmail.com.

(*Manuscript accepted* 11 *October* 2006)

0017-9078/07/0

Copyright © 2007 Health Physics Society

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

water use. This run had the least ^{222}Rn concentration among the other monthly runs. Hightower and Watson concluded that standing water in pipes or the well can have an effect on ^{222}Rn in water measurements. Freyer et al. (1997) found similar variations when sampling from observation wells. They measured a sharp increase of ^{222}Rn in water during initial pumping and assumed this effect was due to mixing of fresh groundwater with older stagnant water in the well.

We continued the investigation of ^{222}Rn in schools with particular interest in spatial and temporal variations of ^{222}Rn concentrations. By measuring ^{222}Rn concentrations in air and water, we determined transfer coefficients to compare against predictions from a model. Multiple detectors were placed in kitchens to detect a variation of the released waterborne ^{222}Rn. Water samples were taken throughout water usage to detect a variation of ^{222}Rn in water concentration.

MATERIALS AND METHODS

Nine elementary/middle schools in Maine were investigated to study water-use simulations with the intent to examine variations of ^{222}Rn in the water over time and spatially in a school kitchen. Simulations were performed at eight schools, school SW was studied twice, and only ^{222}Rn in water measurements were available for the ninth school MR.[†]

The model

A model of ^{222}Rn release was applied where the ^{222}Rn transfer coefficient of a room is given by

$$f = \frac{\Delta C_{\text{air}}}{C_{\text{W}}} = \frac{W\varepsilon}{VT\lambda}, \tag{1}$$

where f is the transfer coefficient, ΔC_{air} is the change in ^{222}Rn concentration in air, C_{w} is the ^{222}Rn concentration in the water being used, W is the total volume of water used in a time T, ε is the total use-weighted emissivity of the faucets running water, V is the volume of the room, and λ is the ventilation rate of the bulk room air. A faucet's emissivity is defined as the fraction of ^{222}Rn released due to aeration. The air is assumed to be well mixed while ventilating. The derivation of this model can be found in Hess et al. (1987) and Hess and Haskell (1994). The predicted transfer coefficients were calculated (f_{calc}) using W, ε, V, T, and λ. For each ^{222}Rn detector in the kitchen, the measured transfer coefficient (f_{meas}) was found by the ratio of ΔC_{air} and $C_{\text{w.}}$ The parameters in the model were measured using the following procedure over the course of a 1-h simulation.

Simulations

In each school kitchen, the sinks and dish-washing sprayers were fully opened to cause a burst of water and release of ^{222}Rn. Multiple water samples were collected over the 1-h simulation from a sink running cold water with a faucet submerged in a overflowing beaker to prevent aeration. Using a syringe, a 10-mL sample from the beaker was injected under 5 mL of mineral oil cocktail (Perkin Elmer Life and Analytic Sciences, Boston, MA) in a 20-mL glass scintillation vial with a polyseal cap (Kimble #74515-20, VWR International, West Chester, PA). The vials were returned to the laboratory and analyzed for ^{222}Rn using a liquid scintillation detector (Packard Tri-Carb 1500; Perkin Elmer Life and Analytic Sciences, Boston, MA) following the standard method recommended by the EPA (AWWA 1996). Water samples were also collected with a syringe from the drain of each sink and sprayer into scintillation vials in order to calculate emissivities. The samples from the drain contain the ^{222}Rn remaining after aeration from the faucet. A non-aerated sample, using the overflowing beaker method, was taken at the same time to determine the original ^{222}Rn concentration. The emissivity is calculated as one minus the ratio of the aerated and non-aerated ^{222}Rn concentrations of water. The total use-weighted emissivity is the sum of the emissivities weighted by the fraction of water used.

The water usage was measured by measuring the volumetric flow rates of each faucet. A beaker of known volume was filled and timed with a stopwatch. This procedure provided the amount of water passing through each sink/sprayer as well as the total volume used during the simulation. These flow rates were measured at least six times during the simulation.

The ^{222}Rn in air measurements were made using Honeywell Professional Radon Monitors (Sun Nuclear, Melbourne, FL). These detectors were placed in kitchens and rooms throughout the school to detect ^{222}Rn released in the kitchen accumulating in other rooms of the school. The detectors were started at least 1 h before the simulation began and logged data for at least 24 h. At school JS, 12 detectors were placed on a surface at mid-level throughout the kitchen (Fig. 1). During a repeat study at school SW, 15 detectors were placed at three vertical levels in the kitchen (Fig. 2). There were five locations where the detectors were placed at the floor, mid, and ceiling levels of the kitchen. With an array of detectors in the kitchen at these two schools, a linear interpolation was implemented to map the ^{222}Rn concentration throughout the room to illustrate horizontal

[†] A electrical power outage after the simulation caused a loss of ^{222}Rn in air data, while the ^{222}Rn in water measurements taken during simulation were unaffected.

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

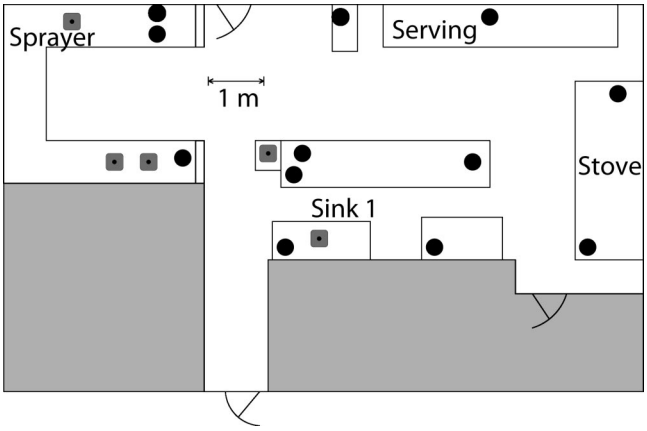

Fig. 1. The floor plan at the school JS kitchen. The circles represent ^{222}Rn detectors and the squares are sinks or sprayers running water. All of the detectors are roughly at kitchen counter height.

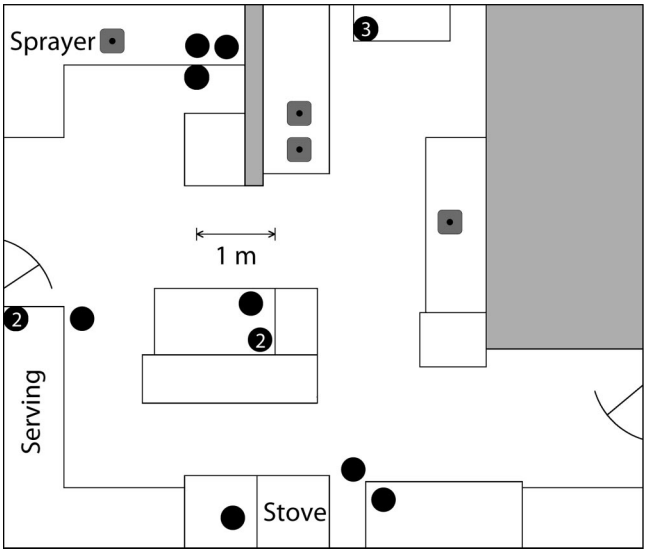

Fig. 2. The floor plan at the school SW kitchen. The circles represent ^{222}Rn detectors and the squares are sinks or sprayers running water. Each detector is either at the floor, mid, or ceiling level, and numbered circles represent the number of overlapping detectors in this aerial view.

and vertical variation. The map represents the spatial distribution of ^{222}Rn at one point in time. The time chosen was the midpoint of the interval over which the detectors show an accumulation of ^{222}Rn due to water use. The known concentrations were placed in a grid, and all the intermediate concentrations were estimated by taking the average of all four nearest neighbors.

An injection of sulfur hexaflouride (SF_6) into the air provided a tracer gas to determine the bulk air ventilation in the room. Air was periodically sampled into 10-L SKC Mylar bags (SKC Inc., Eighty Four, PA) and later analyzed in a Miran Infared Gas Analyzer (Invensys/Foxboro, Foxboro, MA) to measure the SF_6 concentration in each bag. The concentrations were fitted to an exponential decay to calculate the ventilation (decay) rate. The airflow patterns in the room were not measured. The volumes of the kitchens were measured directly with a tape measure.

RESULTS

Table 1 lists the average ^{222}Rn in water concentrations and the range of variation from the start to the end of the simulation. The ^{222}Rn in water measurements increased by a factor of 4 at one school and overall increased by at least 200 Bq L^{-1} (5,400 pCi L^{-1}) at six of the nine schools. No school showed a decrease of ^{222}Rn concentration in water over time. The ^{222}Rn in water concentrations at school JS illustrate a factor of four increase in ^{222}Rn during the simulation (Fig. 3). The two simulations at school SW were separated by 7 d and had similar ^{222}Rn in water measurements (Fig. 4) with a maximum level of 1,780 Bq L^{-1} (48,100 pCi L^{-1}).

The parameters used to determine the calculated transfer coefficients are listed in Table 2. For each school, the length of the simulation, T, was 60 min. The calculated transfer coefficients ranged from 1.6×10^{-4}–665×10^{-4}. The average increase of ^{222}Rn among the detectors present in the kitchens and the measured

Table 1. The average, maximum, and minimum radon in water concentrations measured over 1 h. The error is a 1-sigma standard deviation of the multiple measurements.

	C_w		C_w^{max}		C_w^{min}	
School	(Bq L^{-1})	(pCi L^{-1})	(Bq L^{-1})	(pCi L^{-1})	(Bq L^{-1})	(pCi L^{-1})
JS	1,140 ± 507	30,800 ± 13,700	1,900	51,400	451	12,200
SL	740 ± 161	20,000 ± 4,340	1,030	27,700	543	14,700
CR	703 ± 107	19,000 ± 2,890	839	22,700	524	14,200
DM	203 ± 19	5,490 ± 514	239	6,470	177	4,790
BR	250 ± 17	6,770 ± 459	300	8,120	219	5,910
SW11	1,520 ± 282	41,100 ± 7,620	1,780	48,100	974	26,300
SW18	1,370 ± 311	36,900 ± 8,410	1,730	46,900	1,010	27,300
MR	616 ± 97	16,700 ± 2,630	733	19,800	472	12,800
BL	226 ± 8	6,120 ± 218	237	6,390	209	5,640
LS	768 ± 51	20,800 ± 1,390	843	22,800	624	16,900

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

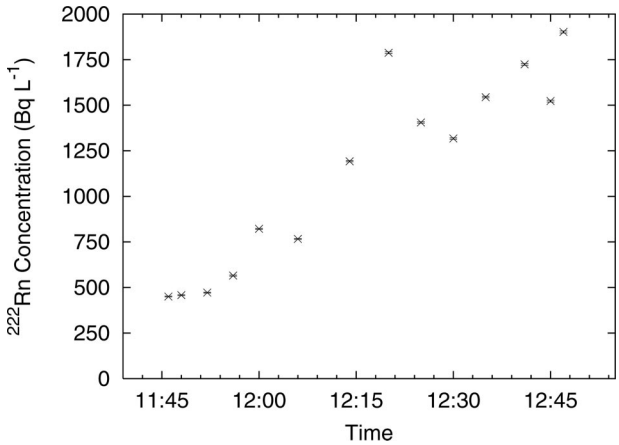

Fig. 3. The ^{222}Rn in water concentrations during water usage at school JS.

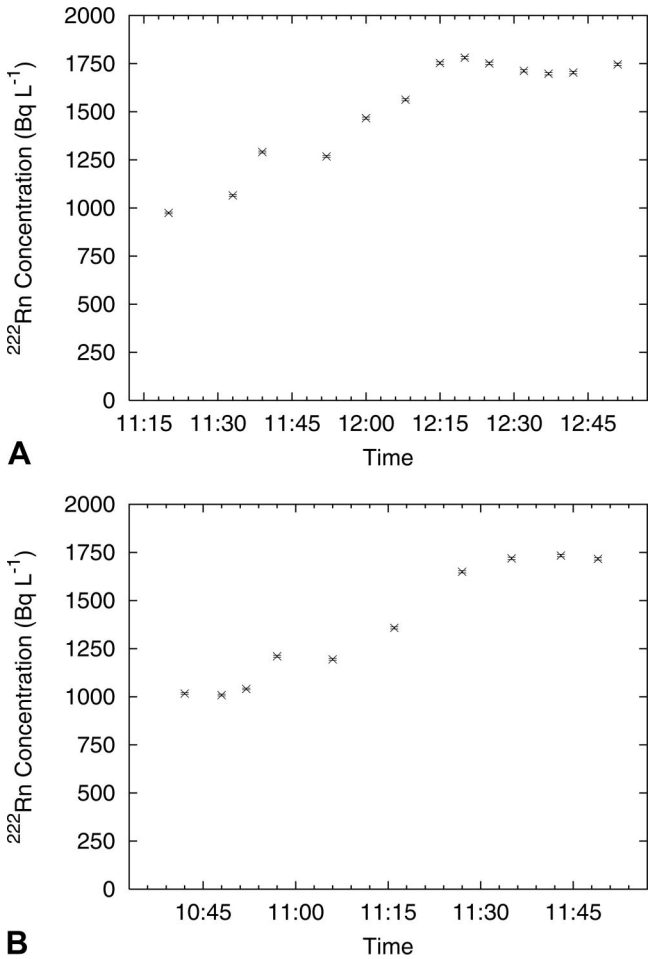

Fig. 4. The ^{222}Rn in water concentrations during water usage at school SW on (a) 11 July 2002 and (b) 18 July 2002.

transfer coefficients are shown in Table 3, which also tabulates the ratio of the calculated and measured transfer coefficients. The average amount of ^{222}Rn released ranged from 0.096–1.96 Bq L^{-1} (2.6–52.9 pCi L^{-1}) across all the school kitchens. Except for school BR, the calculated transfer coefficient was greater than the measured transfer coefficient. The build-up and decay of ^{222}Rn concentration in air for one detector in the kitchen and low concentrations of measured ^{222}Rn in adjacent classrooms can be illustrated by data from school JS (Fig. 5). Except for the kitchen-only study at SW18, the remaining schools had several detectors in other rooms of the school. Table 4 lists the average maximum and background ^{222}Rn in air concentration in the schools' classrooms. The increase in ^{222}Rn in the classrooms was no more than 0.1 Bq L^{-1} (3 pCi L^{-1}) above background during the 24-h measurement period.

In each of the school kitchens, several ^{222}Rn detectors were utilized to measure a spatial variation of the increase of ^{222}Rn concentration in the air due to water usage. The spatial variation was evident in schools JS and SW where the kitchen was studied in detail. The interpolated results from the JS kitchen are contoured in Fig. 6. This figure demonstrates a horizontal variation of ^{222}Rn in the kitchen ranging from 0.75–4 Bq L^{-1} (20–108 pCi L^{-1}). The vertical variation of released ^{222}Rn is evident at school SW. Fig. 7a shows the ^{222}Rn concentration at the dish-washing sprayer. The detector placed at the mid level (the same height as the sprayer itself) recorded the largest ^{222}Rn concentration of 1.1 Bq L^{-1} (30 pCi L^{-1}). However, at the stove, the furthest location from any water usage, the highest ^{222}Rn concentration measured was 0.65 Bq L^{-1} (18 pCi L^{-1}) by the detector closest to the ceiling (Fig. 7b). The interpolated concentrations (Fig. 8) illustrate the variation of ^{222}Rn concentrations throughout the kitchen for the mid, 0.20–0.70 Bq L^{-1} (5.4–19 pCi L^{-1}), and ceiling, 0.35–0.55 Bq L^{-1} (9.5–15 pCi L^{-1}), levels. The detectors on the floor measured ^{222}Rn concentrations of 0.13–0.48 Bq L^{-1} (3.5–13 pCi L^{-1}).

DISCUSSION

The ^{222}Rn in water concentration significantly increased at six of the schools during the course of the simulation. A short-term temporal variation was reproduced at school SW, which was likely due to similar purging or water-usage history for the sample days. Though the plumbing in the school and mixing in water tanks could cause the observed increase in ^{222}Rn concentrations, we do not believe that this is the case. The measurements that demonstrate the ^{222}Rn variation were always collected from a dedicated sink by slowly drawing cold water. Within 5 min of starting the simulation, a thermometer indicated that the water temperature dropped and held constant at 11°C, which indicates the

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

Table 2. The volume V, ventilation rate λ, water used W, total use-weighted emissivity ε, and the calculated transfer coefficient f_{calc}. The error is a 1-sigma uncertainty in the measurement.

School	V (L)	λ (min^{-1})	W (L)	ε	f_{calc} ($\times 10^{-4}$)
JS	137,000	0.0183 ± 0.003	2,369 ± 76	0.55 ± 0.02	86.7 ± 14.2
SL	169,000	0.0481 ± 0.003	2,582 ± 73	0.25 ± 0.01	13.4 ± 1.1
CR	14,000	0.0302 ± 0.004	3,271 ± 52	0.52 ± 0.01	665 ± 93
DM	163,000	0.0604 ± 0.009	2,010 ± 101	0.31 ± 0.03	10.7 ± 2.0
BR	74,200	0.1076 ± 0.011	177 ± 5	0.42 ± 0.01	1.6 ± 0.2
SW11	131,000	0.1786 ± 0.002	2,707 ± 126	0.51 ± 0.02	9.9 ± 0.6
SW18	131,000	0.1129 ± 0.022	2,672 ± 66	0.44 ± 0.01	13.2 ± 2.6
BL	184,000	0.1248 ± 0.026	2,597 ± 163	0.53 ± 0.04	9.9 ± 2.3
LS	130,000	0.2800 ± 0.078	2,188 ± 45	0.57 ± 0.01	5.7 ± 1.6

Table 3. The number of radon-in-air detectors placed in each kitchen along with the average increase in radon concentration, the measured transfer coefficient and the ratio of the calculated and measured transfer coefficients. The error is a 1-sigma standard deviation of multiple measurements.

School	Number of detectors	$\Delta\overline{C}_{air}$ (Bq L^{-1})	$\Delta\overline{C}_{air}$ (pCi L^{-1})	$\bar{f}_{meas}$ ($\times 10^{-4}$)	$f_{calc}/\bar{f}_{meas}$
JS	12	1.960 ± 0.971	52.9 ± 26.3	17.2 ± 8.5	5.0 ± 2.6
SL	3	0.511 ± 0.122	13.8 ± 3.3	6.9 ± 1.6	1.9 ± 0.5
CR	2	0.706 ± 0.315	19.1 ± 8.5	10.0 ± 4.5	66.5 ± 31.0
DM	3	0.130 ± 0.032	3.4 ± 0.9	6.2 ± 1.6	1.7 ± 0.5
BR	3	0.160 ± 0.130	4.4 ± 3.5	6.5 ± 5.1	0.2 ± 0.2
SW11	4	0.330 ± 0.300	9.0 ± 8.1	2.2 ± 2.0	4.5 ± 4.1
SW18	15	0.403 ± 0.320	10.9 ± 8.6	3.0 ± 2.3	4.5 ± 3.6
BL	7	0.096 ± 0.096	2.6 ± 2.6	4.2 ± 4.2	2.3 ± 2.4
LS	7	0.250 ± 0.170	6.8 ± 4.6	3.3 ± 2.2	1.7 ± 1.3

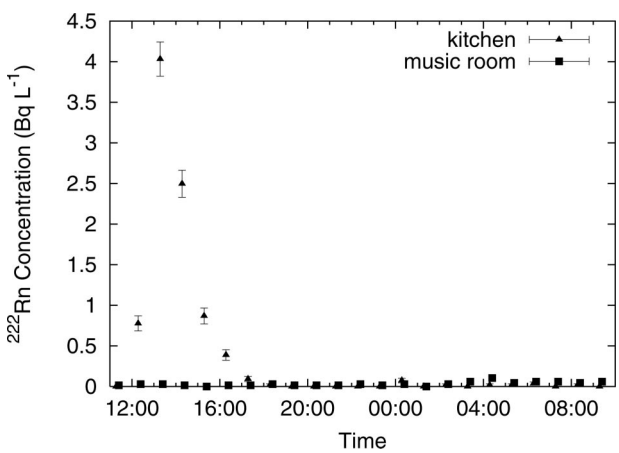

Fig. 5. The ^{222}Rn in air concentrations from one detector in the kitchen and one in the music room at school JS. The simulation occurred with water running from 11:45–12:45.

origin of water to be solely groundwater and not the warmer water within the school plumbing system. We suspect that this could be due to initially drawing older well water before reaching radon-rich groundwater. The water-usage history affects the ^{222}Rn concentration indicating that if a measurement was made in these schools for a routine ^{222}Rn in water measurement, the results would heavily depend on how much water had been recently drawn from the well.

The spatial variation of ^{222}Rn observed at school JS indicates a movement of ^{222}Rn not predicted by the model. The largest ^{222}Rn concentration occurred at the location of sink 1, which had the largest emissivity. The lowest concentration occurred in the furthest corner of the kitchen by the serving counter away from any water sources. It is clear that ^{222}Rn is not perfectly mixed within the kitchen, and the largest concentrations are found near some water sources. Since areas far from the water sources are not accumulating as much ^{222}Rn concentration, the ^{222}Rn evidently did not spread out horizontally. The dual-level variations observed at school SW provide an explanation of the movement of ^{222}Rn through the kitchen. The largest ^{222}Rn concentration of 0.7 Bq L^{-1} (19 pCi L^{-1}) was observed near the sprayer, while elsewhere at that level the concentration was near 0.2 Bq L^{-1} (5.4 pCi L^{-1}), which indicates there was little horizontal movement of ^{222}Rn at the mid level. An intermediate amount of ^{222}Rn at 0.4–0.5 Bq L^{-1} (11–13.5 pCi L^{-1}) covered most of the ceiling level. The ^{222}Rn concentrations at this level were more evenly distributed, which indicates that the waterborne ^{222}Rn is moving mainly upward, not horizontally, from the running water. These results suggest that studies of released ^{222}Rn from water are complicated by heterogeneous distribution of ^{222}Rn and require multiple detectors throughout the room, both horizontally and vertically.

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

Table 4. The number of rooms measured and their average maximum and background radon concentrations. The error is a 1-sigma standard deviation of multiple measurements.

School	Number of rooms	$\bar{C}_{air}^{max}$ (Bq L^{-1})	$\bar{C}_{air}^{max}$ (pCi L^{-1})	$\bar{C}_{air}^{background}$ (Bq L^{-1})	$\bar{C}_{air}^{background}$ (pCi L^{-1})
JS	3	0.079 ± 0.023	2.1 ± 0.6	0.024 ± 0.004	0.7 ± 0.1
SL	9	0.110 ± 0.021	2.8 ± 0.6	0.036 ± 0.008	1.0 ± 0.2
CR	12	0.120 ± 0.040	3.2 ± 1.1	0.032 ± 0.010	0.9 ± 0.3
DM	10	0.220 ± 0.140	6.1 ± 3.7	0.120 ± 0.090	3.1 ± 2.4
BR	12	0.094 ± 0.026	2.6 ± 0.7	0.031 ± 0.004	0.8 ± 0.1
SW11	9	0.091 ± 0.072	2.4 ± 1.9	0.030 ± 0.024	0.8 ± 0.7
BL	8	0.070 ± 0.020	1.9 ± 0.5	0.020 ± 0.006	0.5 ± 0.2
LS	8	0.096 ± 0.034	2.6 ± 0.9	0.028 ± 0.007	0.8 ± 0.2

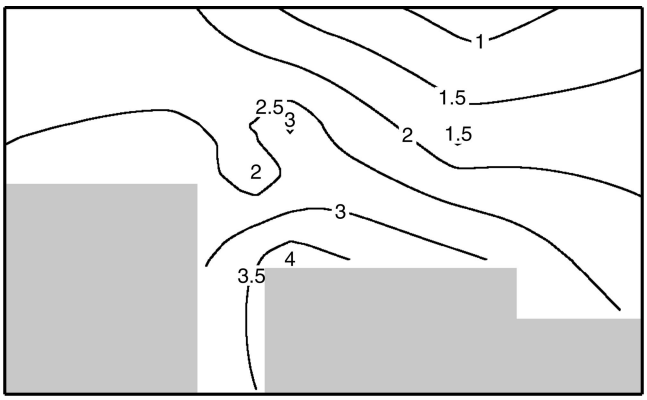

Fig. 6. The interpolated ^{222}Rn in air measurements (in Bq L^{-1}) at 13:10 at the school JS kitchen.

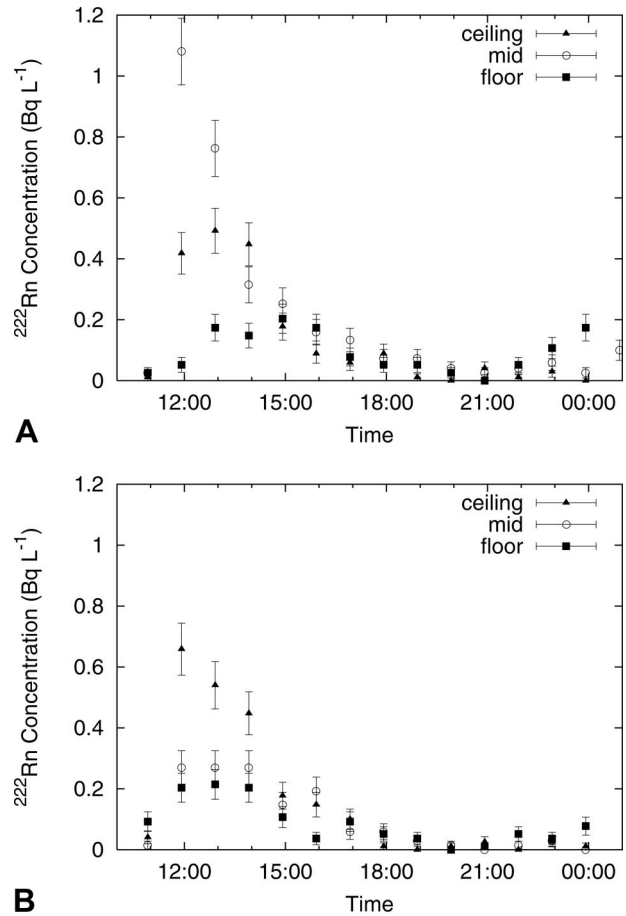

Fig. 7. The ^{222}Rn in air concentration from three detectors at separate levels (a) near the sprayer and (b) near the stove in the kitchen at school SW. The simulation occurred with water from 10:45–11:45.

In all but one case (school BR), the calculated was higher than the measured transfer coefficient. This discrepancy suggests that either the model used to calculate the transfer coefficient overestimates the released ^{222}Rn or not all of the released ^{222}Rn was measured. This latter point was the impetus for placing several detectors in the kitchen to ensure that all released ^{222}Rn was measured. It is clear from our results that a heterogeneous distribution of ^{222}Rn exists in the kitchen after water usage. The model took into account a ventilation rate of the kitchen but assumed the ^{222}Rn was well mixed. The actual airflow pattern in the room was not known, however, it may explain the heterogeneous ^{222}Rn distribution. If ^{222}Rn was following the airflow pattern and exiting ventilation openings instead of uniformly mixing, the ^{222}Rn loss due to ventilation would be greater then predicted. Therefore, the model would overestimate the ^{222}Rn release.

School BR was the only case with a measured transfer coefficient greater than the calculated value. At this school we were warned of a low yield well and used a lower amount of water than typically used. Since the model assumed a large burst of waterborne ^{222}Rn in a short amount of time, it seemed to fail when the water usage was small over the duration of the simulation. School CR had a calculated transfer coefficient much higher than the measured, by a factor of 66. This school had the smallest kitchen volume compared to the others. It is possible that the released ^{222}Rn continued to occupy a larger volume of air in nearby spaces (above drop ceiling, closets). These extra volumes would not be a

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

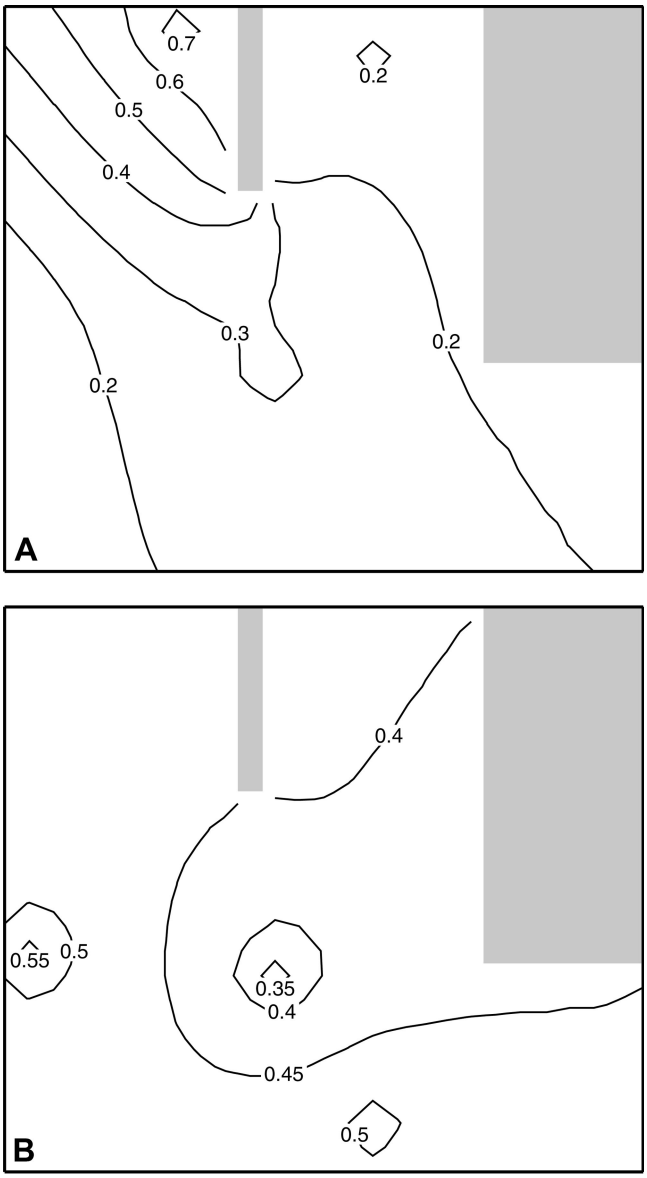

Fig. 8. The interpolated ^{222}Rn in air measurements (in Bq L^{-1}) at 12:55 at the (a) mid and (b) ceiling level at the school SW kitchen.

significant contribution to a kitchen of large enough volume. Using a small room volume for school CR explains why the model predicted a higher ^{222}Rn concentration and transfer coefficient due to the volume dependence in eqn (1).

In general, very little ^{222}Rn was measured in the adjacent and distant classrooms of the schools. This means that any ^{222}Rn leaving the kitchen was diluted with the air in the rooms measured. The average maximum ^{222}Rn concentrations generally were below the 0.15 Bq L^{-1} (4 pCi L^{-1}) action level. At school DM, the maximum concentrations did measure higher than the action level in some classrooms, but the average background concentrations were also high. These maximum concentrations were found during the 24-h measurement period after the simulation. Any ^{222}Rn from soil gas and building materials can build up in classrooms overnight while the building is closed and inactive, and so the rises in concentration measured may not be entirely due to waterborne ^{222}Rn.

CONCLUSION

By placing ^{222}Rn-in-air detectors throughout a kitchen and a school, we were able to track the release of ^{222}Rn while running water provided a burst of ^{222}Rn in the kitchen. Even though the amount of ^{222}Rn found in the kitchen after water usage always exceeded the 0.15 Bq L^{-1} (4 pCi L^{-1}) action level, we found little ^{222}Rn accumulation moving to the other, student-occupied rooms in the school. Inside the kitchen, however, a spatial variation of the ^{222}Rn concentration existed throughout the room following water usage. For the two schools measured in detail, variations between 0.75–4.0 Bq L^{-1} (20–108 pCi L^{-1}) and 0.2–0.7 Bq L^{-1} (5.4–19 pCi L^{-1}) were found. Thus, to accurately measure the ^{222}Rn accumulation in a room due to water usage, more than one detector is required. In addition, measurements of the air flow pattern would assist in making better conclusions about how well the room air mixes and where to place ^{222}Rn detectors. More than half of the schools studied showed a significant (>200 Bq L^{-1}) increase in dissolved ^{222}Rn in water concentration during 1 h of running water. To get a better representation of the groundwater's ^{222}Rn concentration, several measurements while pumping are needed with knowledge of water-use history to prevent from exclusively measuring older, decayed standing water in the well.

Acknowledgments—This work was partially supported by U.S. Environmental Protection Agency grants # IW-2645-NAEX and # X-82918201-0, State of Maine grant # 402076, and the University of Maine. The authors would like to thank Jason Grant for fieldwork.

REFERENCES

American Water Works Association. Standard methods for the examination of water and wastewater: 7500-RN radon. Washington, DC: American Water Works Association and Public Health Association; 1996.

Duncan DL, Gesell TF, Johnson RH Jr. Radon-222 in potable water. In: Proceedings of the Health Physics Society Tenth Mid-Year Symposium on Natural Radioactivity in Man's Environment. Troy, NY: Renssaelaer Polytechnic Institute Press; CONF-761031; 1977: 340–357.

Eisenbud M, Gesell TF. Environmental radioactivity from natural, industrial, and military sources. San Diego: Academic Press; 1997.

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.

Freyer K, Treutler HC, Dehnert J, Nestler W. Sampling and measurement of radon-222 in water. J Environ Radioactivity 37:327–337; 1997.

Hess CT, Haskell LE. A comparison of two pathways to human for radon from drinking water: inhalation and ingestion. In: Wang RGM, ed. Water contamination and health: integration of exposure assessment, toxicology, and risk assessment. New York: Marcel Dekker, Inc; 1994: 167–197.

Hess CT, Weiffenbach CV, Norton SA. Variations of airborne and waterborne Rn-222 in houses in Maine. Environment International 8:59–66; 1982.

Hess CT, Vietti MA, Mage DT. Radon from drinking water. In: Hemphill DD, ed. Trace substances in environmental health–XXI. Columbia, MO: University of Missouri Press; 1987: 158–171.

Hightower JH, Watson JE. ^{222}Rn in water: a study of two sample collection methods, effects of mailing samples and temporal variation of concentrations in North Carolina groundwater. Health Phys 69:219–226; 1995.

Lachapelle EB. A study of radon-222 from potable water sources to household air. Orono: University of Maine; 1988. Thesis.

Norris MJ, Guiseppe VE, Hess CT. Waterborne radon in seven Maine schools. Health Phys 86:528–535; 2004.

Prichard HM, Gesell TF. An estimate of population exposures due to radon in public water supplies in the area of Houston, Texas. Health Phys 41:599–606; 1981.

U.S. Environmental Protection Agency. National primary drinking water regulations; radon-222; proposed rule. Fed Reg 64(211); 1999. Available at http://www.epa.gov/safewater/radon/proposal.html. Accessed 14 October 2005.

■ ■

Copyright © by the Health Physics Society. Unauthorized reproduction of this article is prohibited.