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# A Study of Radon in Air and Water in Maine Schools

Mary Jo Norris

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# **A STUDY OF RADON IN AIR AND WATER IN MAINE SCHOOLS**

By

**Mary Jo Norris**

B.S. Cleveland State University, 1998

**A THESIS**

Submitted in Partial Fulfillment of the

Requirements for the Degree of

**Master of Science**

(in Physics)

**The Graduate School**

**The University of Maine**

August, 2002

**Advisory Committee:**

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# A STUDY OF RADON IN AIR AND WATER IN MAINE SCHOOLS

By Mary Jo Norris

Thesis Advisor: Dr. C. T. Hess

An Abstract of the Thesis Presented  
in Partial Fulfillment of the Requirements for the  
Degree of Master of Science  
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August, 2002

The transfer coefficient of radon from water to air was investigated in schools. Kitchens, bathrooms and locker rooms were studied for seven schools in Maine. Simulations were done in water-use rooms where radon in air detectors were in place. Quantities measured were radon in water ( $270\text{--}24500 \frac{\text{pCi}}{\ell}$ ) and air ( $0\text{--}80 \frac{\text{pCi}}{\ell}$ ), volume of water used, emissivities ( $0.01\text{--}0.99$ ) and ventilation rates ( $0.012\text{--}0.066 \frac{1}{\text{min}}$ ). Variation throughout the room of the radon concentration was found. Values calculated for the transfer coefficient for kitchens and baths were ranged from  $9.6 \times 10^{-6}$  to  $2.0 \times 10^{-2}$ . The transfer coefficient was calculated using these parameters and was also measured using concentrations of radon in water and air. This provides a means by which radon in air can be estimated using the transfer coefficient and the concentration in the water in other schools and it can be used to estimate the dose caused by radon released from water use. This project was partially funded by the United States Environmental Protection Agency (grant #X82812101-0) and by the State of Maine (grant #10A500178). These are the first measurements of this type to be done in schools in the United States.

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# 1 BACKGROUND

Radon\* ( $^{222}\text{Rn}$ ) is a naturally occurring radioactive gas formed in the decay chain of uranium ( $^{238}\text{U}$ ), as shown in Figure 1.1. It is a noble gas and has a half-life of 3.82 days. Also formed in this series is radium† ( $^{226}\text{Ra}$ ). Both  $^{226}\text{Ra}$  and  $^{238}\text{U}$  can be found in certain types of rocks, such as granites, gneisses, phosphatic rocks and marine shales.<sup>1</sup> Uranium and radium concentrations in soil and rock vary by geographical region. Maine has many areas where granites and other types of rock can be found having high concentrations of radium, with granites that have up to 25 ppm of uranium.<sup>2</sup>  $^{238}\text{U}$  decays into  $^{226}\text{Ra}$ , which in turn produces  $^{222}\text{Rn}$ . Because  $^{222}\text{Rn}$  is chemically inert, radon gas will percolate through the soil and be released into the atmosphere causing a concentration of radon in outside air. However, because the radon is mixing with large amounts of outside air, the concentration is small. The United States Environmental Protection Agency (EPA) estimates that the average value of  $^{222}\text{Rn}$  in outside air in the United States is  $0.40 \frac{\text{pCi}}{\ell}$ .<sup>3</sup> Eisenbud and Gesell note that radon in outside air varies by region, time of year, and meteorological conditions, with a range of 0.22 to  $0.30 \frac{\text{pCi}}{\ell}$  as average in the United States.<sup>1</sup> The average value of radon in air over a summer in Manitoba and Saskatchewan, Canada was as high as  $1.6 \frac{\text{pCi}}{\ell}$ .<sup>1</sup>

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\*The terms radon and uranium in this thesis will refer to the isotopes  $^{222}\text{Rn}$  and  $^{238}\text{U}$ , respectively.

†The term radium in this thesis will refer to the isotope  $^{226}\text{Ra}$ .

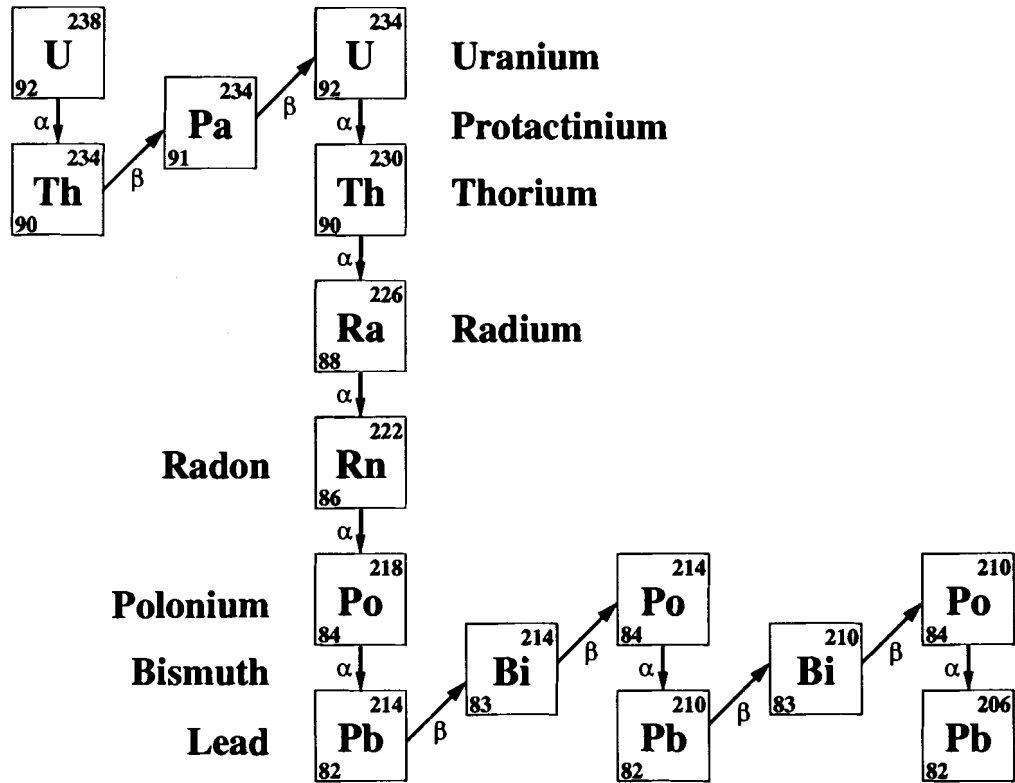


Figure 1.1: Uranium Decay Series

On the contrary, inside a building, radon can accumulate, if there is little ventilation. Radon in the soil gas can enter a building through cracks in the foundation. Water supplies can also be contaminated when  $^{222}\text{Rn}$  leaches out of the rocks and soil into the water. As water is used by different appliances, the radon is liberated into indoor air. Another source of radon is building materials such as plaster board and concrete containing  $^{226}\text{Ra}$ . Of the sources of radon, the most significant contributor to an increased concentration to indoor air is soil gas, but water can become a significant source in areas with large amounts of radon in water.<sup>1</sup>

$^{222}\text{Rn}$  is known to be a health hazard. One of the earliest indications of the health risk that  $^{222}\text{Rn}$  poses, was found in the 1940's, when it was linked to lung cancer in uranium miners.<sup>4</sup> According to the Environmental Protection Agency,  $^{222}\text{Rn}$  is the second leading cause of lung cancer in the United States, smoking being the first.<sup>5</sup> As radon in air decays, its progeny stick to dust particles in the air and other aerosols. When this air is inhaled, the progeny sticks to lung tissue and the radon will be partially absorbed by lung tissue.<sup>1</sup> In successive decays of the radon and its progeny, energetic alpha particles are produced from the decay of the polonium daughters (shown in Figure 1.1). The alpha particles penetrate the lung tissue resulting in a radiation dose.

The EPA suggests that nearly 87 percent of the health risk due to waterborne radon is due to inhaling the gas as it is released into the air as water is used.<sup>3</sup> Currently, the EPA has an action level of  $4 \frac{\text{pCi}}{\ell}$  for radon in air. A new standard is being proposed by the EPA for radon in water. A maximum contaminant level (MCL) of  $300 \frac{\text{pCi}}{\ell}$  was proposed by the EPA. However, the public response suggested the level be set between 30 and 20,000  $\frac{\text{pCi}}{\ell}$  with a majority agreeing the standard should be higher than the proposed MCL of  $300 \frac{\text{pCi}}{\ell}$ .<sup>3</sup> To this end, a research group in the Department of Physics and Astronomy at The University of Maine conducted a 100 house study of radon in water in private homes in Maine, funded by the EPA.<sup>6</sup> A current project studies the effects of  $^{222}\text{Rn}$  in water in public places such as businesses

and schools. This thesis presents the results from the first seven schools studied in this project.

The transfer coefficient is defined as the ratio of the concentration of radon in air (from water-use) to the concentration of radon in water. In 1980, Gessell and Prichard made the first estimate of  $\sim 1 \times 10^{-4}$  for the transfer coefficient.<sup>3</sup>

Hess *et al.*<sup>2</sup> measured radon in air for 100 houses in Maine from October 1980 to May 1981 using track-etch cups placed in five different locations in each house. Track-etch cups are a passive measuring device that are left in place for months at a time to detect radon. They consist of a small piece of plastic inside a cup covered by a filter that allows radon gas to enter the cup. The radon decays and its progeny produce alpha particles that react with the plastic, making a defect site. The plastic is then chemically etched so that each defect site is eroded further to make a pit. The pits are then counted and from this an average value of radon in air can be obtained.

Hess *et al.*<sup>2</sup> found concentrations of radon in air in the range of 0.05-135  $\frac{\text{pCi}}{\text{l}}$ . From these measurements, they found a correlation between radon in air and radon in water, namely, a water supply with a radon concentration of 10,000  $\frac{\text{pCi}}{\text{l}}$  would result in approximately 1.07  $\frac{\text{pCi}}{\text{l}}$  of radon in air.<sup>2</sup> This corresponds to a transfer coefficient of  $1.07 \times 10^{-4}$ . Dynamic measurements of the radon in air were also made, during which time the residents of the house made a log of all major water uses. The ventilation rate of the house was determined using the dynamic radon measurements. It was determined that the amount of radon present in the air from water was inversely

proportional to the ventilation rate. The group found a transfer of  $0.8 \pm 0.2 \frac{pCi}{\ell}$  of radon in air for water with a radon concentration of  $10,000 \frac{pCi}{\ell}$  in a house with a ventilation rate of one air exchange per hour.<sup>2</sup>

In 1988, LaChapelle<sup>7</sup> made measurements of the transfer coefficient in 40 houses in Maine. Twenty four hours of water use was simulated in a period of two hours in each house, creating a radon burst. Radon in air, volume of the room, ventilation rate, emissivity of the appliances used, and total water usage were measured in each house. Using these quantities, LaChapelle found an average value of  $1.63 \times 10^{-4}$  for the transfer coefficient in houses in his study.<sup>7</sup>

Grodzins *et al.*<sup>8</sup> made radon in air measurements for every school in Maine. They made measurements of every room on the ground level and below for each school. These data, however, were taken mostly on the weekend, when schools were closed and do not provide a representation of the amount of radon present in schools on a day-to-day basis.

Bernhardt and Hess<sup>9</sup> measured exposure due to showering by measuring the release of radon from the shower and the growth of its progeny. They found that a shower emits 75% of the radon in the water.<sup>9</sup> They also found that 85% of the potential alpha energy is contained within water aerosols that are small enough to inhale.<sup>9</sup>

A research group with the Connecticut Department of Public Health and the EPA conducted a study of 217 schools in Connecticut.<sup>10</sup> They found that over 52% of the schools tested had at least one room with radon concentrations over the action level



of  $4 \frac{\text{pCi}}{\ell}$ .<sup>10</sup> The concentrations of radon in water in the schools ranged from 100 to 20,900  $\frac{\text{pCi}}{\ell}$  in their study.<sup>10</sup> Showers in schools were tested by running water and placing radon monitors near the showers. Showers with less than 400  $\frac{\text{pCi}}{\ell}$  of radon did not show an increase to radon in air and showers greater than 10,000  $\frac{\text{pCi}}{\ell}$  showed a definite increase in the radon in air.<sup>10</sup> The group found variation of greater than 50%, in some cases, of the amount of radon in water and suggests that at least two water samples be taken, preferably in different seasons, to get a more accurate measurement.<sup>10</sup>

Data from the seven schools tested in this thesis project were used to investigate the transfer of radon from water to air. This thesis project was a field study and also a modeling exercise.

## 2 MASS FLOW THEORY

Mass flow theory<sup>7,11</sup> is used to describe the concentration of radon indoors. Sources of radon in a building are from outside air, soil gas entering from the basement, water use, and building materials. The mass flow theory uses a differential equation to relate the concentration of radon in the air to the methods by which radon enters and exits a building. From this differential equation, the concentration of radon in the air due to water use can be found and from this, an expression for the transfer coefficient,  $f$ , is obtained.

The total radon concentration,  $C(t)$ , inside a building of volume,  $V$ , as a function of time is given by

$$\frac{dQ}{dt} + \frac{dV_w}{dt} \epsilon C_w + \frac{dV_a}{dt} C_a + \frac{dV_b}{dt} C_b - \frac{dV_a}{dt} C - \frac{dV_b}{dt} C = V \frac{dC}{dt} + VC\lambda_r. \quad (2.1)$$

$\frac{dQ}{dt}$  is the background activity of radon indoors coming from the building materials.  $Q$  is given by the product of the volume of indoor air and the background concentration of  $^{222}\text{Rn}$  indoors.  $C_w$ ,  $C_a$ , and  $C_b$  are the concentrations of radon in the water, outside air, and the basement, respectively. The emissivity is the fraction of radon that is released from a volume of water and is  $\epsilon$  in equation 2.1.  $\lambda_r$  is the decay constant for radon, which is  $0.00756 \frac{1}{hr}$ , using a half-life of 3.82 days. Figure 2.1 illustrates the terms in equation 2.1 inside a building from all sources.

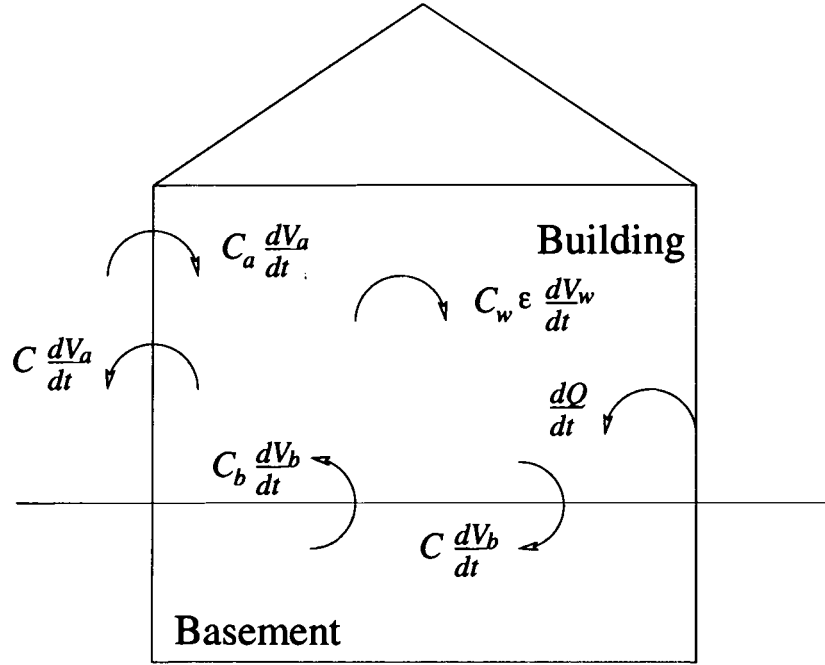


Figure 2.1: Sources of Radon Gas in a Building

Using figure 2.1, one can identify the terms in equation 2.1. Each term has units of activity per time.  $\frac{dQ}{dt}$  is the time rate of change of the amount of radon that comes in as background from building materials.  $\frac{dV_w}{dt} C_w \epsilon$ ,  $\frac{dV_a}{dt} C_a$ , and  $\frac{dV_b}{dt} C_b$  are all of the form of a time rate of change of volume multiplied by a concentration of radon. They give the rate at which radon that enters the building from the water, outdoor air and the basement, respectively. The terms  $\frac{dV_a}{dt} C$  and  $\frac{dV_b}{dt} C$  are the time rate of change of the amount of radon *leaving* the building. The concentration,  $C$ , is used here because the air that is leaving has the total concentration of  $^{222}\text{Rn}$  in the building.  $V \frac{dC}{dt}$  is the time rate of change of the concentration of radon in the building with volume,  $V$ . And finally,  $VC\lambda_r$  is the rate at which radon decays, thereby leaving the building.

Each time water is used, radon is released into the air. The rate at which the radon is released into the building, as water is used, can be expressed as

$$\sum_i \varepsilon_i \frac{dV_{w_i}}{dt} = \sum_i \varepsilon_i W_i \delta(t - t_i). \quad (2.2)$$

$W_i$  is the volume of water used in a short time interval centered around  $t_i$  by an appliance with emissivity,  $\varepsilon_i$ . Multiplying  $W_i$  by the delta function,  $\delta(t - t_i)$ , gives an approximate rate of water use ( $\frac{\text{volume}}{\text{time}}$ ) at time,  $t_i$ . Summing on  $i$  gives the total rate at which radon is released into the building from all water uses,  $i$ .

Integrating equation 2.1 from  $t = 0$  to  $t = T$ , dividing by  $V$ , using the initial condition that  $C = C_o$ , and that  $C = C(T)$  at  $t = T$ , gives

$$\begin{aligned} C(T) = C_o + \frac{C_w}{V} \int_0^T \sum_i W_i \varepsilon_i \delta(t - t_i) dt + \int_0^T C_a \lambda_a dt + \\ + \int_0^T C_b \lambda_b dt - \int_0^T C \lambda dt + \frac{1}{V} \int_0^T \frac{dQ}{dt} dt. \end{aligned} \quad (2.3)$$

Expressions for the decay constants used in equation 2.3 are given by

$$\begin{aligned} \lambda_a &= \frac{\frac{dV_a}{dt}}{V} \\ \lambda_b &= \frac{\frac{dV_b}{dt}}{V} \\ \lambda &= \lambda_a + \lambda_b + \lambda_r. \end{aligned} \quad (2.4)$$

The decay constants are the rates at which air leaves the building into the basement ( $\lambda_b$ ) or the outside air ( $\lambda_a$ ).  $\lambda_r$  is the rate at which the radon “escapes” by decay. The sum of these gives the rate at which the volume of the building is ventilated.

The use-weighted emissivity is

$$\bar{\varepsilon} = \sum_i \frac{W_i \varepsilon_i}{W},$$

where  $W = \sum_i W_i$ . (2.5)

Using  $\bar{\varepsilon}$ , dividing by  $T$ , and integrating equation 2.1 yields

$$\frac{C(T)}{T} = \frac{C_o}{T} + \frac{C_w W \bar{\varepsilon}}{V T} + \overline{C_a \lambda_a} + \overline{C_b \lambda_b} - \overline{C \lambda} + \overline{\left(\frac{dQ}{dt}\right)}. \quad (2.6)$$

The following equations show the time averaged expressions used in writing equation 2.6.

$$\overline{C_a \lambda_a} = \frac{1}{T} \int_0^T C_a \lambda_a dt \quad (2.7)$$

$$\overline{C_b \lambda_b} = \frac{1}{T} \int_0^T C_b \lambda_b dt \quad (2.8)$$

$$\overline{C \lambda} = \frac{1}{T} \int_0^T C \lambda dt \quad (2.9)$$

$$\overline{\left(\frac{dQ}{dt}\right)} = \frac{1}{T} \int_0^T \frac{dQ}{dt} dt \quad (2.10)$$

Now, consider a time,  $T_o$ , when the concentration,  $C(T_o)$ , equals the initial concentration,  $C_o$  and  $W = 0$ . This happens before there is any water use and the radon concentration in the building is at its background level. Letting  $C(T_o) = C_o$  and  $W = 0$  in equation 2.6 gives

$$\overline{C_o \lambda} = \overline{C_b \lambda_b} + \overline{C_a \lambda_a} + \frac{\overline{\left(\frac{dQ}{dt}\right)}}{V}. \quad (2.11)$$

Consider another time,  $T$ , when  $C(T) = C_o$ , only for this case,  $W \neq 0$ . This will be after water has run and the radon in the building comes back down to background. Letting  $C(T_f) = C_o$  in equation 2.6 yields

$$\overline{C_f \lambda} = \frac{C_w W \bar{\epsilon}}{V T} + \overline{C_b \lambda_b} + \overline{C_a \lambda_a} + \frac{\overline{\left(\frac{dQ}{dt}\right)}}{V}. \quad (2.12)$$

Assuming that  $\lambda$  is a constant over the time of the water-use period,  $\overline{C \lambda} = \bar{C} \bar{\lambda}$  and we can re-write equations 2.11 and 2.12 as

$$\bar{C_o} \bar{\lambda} = \overline{C_b \lambda_b} + \overline{C_a \lambda_a} + \frac{\overline{\left(\frac{dQ}{dt}\right)}}{V} \quad (2.13)$$

$$\bar{C_f} \bar{\lambda} = \frac{C_w W \bar{\epsilon}}{V T} + \overline{C_b \lambda_b} + \overline{C_a \lambda_a} + \frac{\overline{\left(\frac{dQ}{dt}\right)}}{V}. \quad (2.14)$$

Equation 2.13 is an expression for  $W = 0$ , before water is run and equation 2.14 is the result of water being used. Subtracting equation 2.14 from 2.13 gives

$$\bar{C_f} \bar{\lambda} - \bar{C_o} \bar{\lambda} = \frac{C_w W \bar{\epsilon}}{V T}. \quad (2.15)$$

Dividing equation 2.15 by  $\lambda$  gives the change in concentration of radon in the air due to water use,  $\Delta C_{air}$ .

$$\Delta C_{air} = \bar{C}_f - \bar{C}_o = \frac{C_w W \bar{\epsilon}}{V T \lambda} \quad (2.16)$$

Dividing the expression for  $\Delta C_{air}$  by  $C_w$  yields the transfer coefficient,  $f$ .

$$f = \frac{\Delta C_{air}}{C_w} = \frac{W \bar{\epsilon}}{V T \lambda} \quad (2.17)$$

The transfer coefficient,  $f$ , can be found by measuring the total water used,  $W$ , the use-weighted emissivity,  $\bar{\epsilon}$ , which is found by measuring the water used by each appliance and the emissivity of that appliance, the volume of the building,  $V$ , the time over which the water is used,  $T$ , and the ventilation rate  $\lambda$ . It can also be found by measuring the change in concentration of radon in the air,  $\Delta C_{air}$  and the concentration of radon in the water,  $C_w$ .

### 3 PROCEDURE

#### 3.1 Study Strategy

To begin our study of the transfer coefficient, preliminary measurements were made at The University of Maine. Detectors were set up in water use rooms to see if radon released from water use could be detected. We found  $270 \frac{\text{pCi}}{\ell}$  in the water at The University of Maine. It was determined that a quantity larger than  $270 \frac{\text{pCi}}{\ell}$  would produce a signal that was easier to detect. Schools for this study with high radon in water were chosen. After collecting data at several schools, it was determined that a  $^{222}\text{Rn}$  concentration in water of around  $5000 \frac{\text{pCi}}{\ell}$  or higher would produce a large enough signal for our equipment to detect.

A list of radon in water values for many schools in Maine was obtained from the State of Maine Department of Human Services, Division of Health Engineering. Some of the measurements on the list were taken as early as 1989 and some were as recent as 1999. Schools were chosen from this list and a request to do testing was made to the principal or superintendant. In some cases, the amount of radon in the schools was much lower than what the value on the list from the State had indicated and the radon signal during the simulation was often difficult to see. When possible, we would try to get a sample of water to measure the  $^{222}\text{Rn}$  concentration before doing a simulation at a school.

In some cases, as in the Nickerson School in Swanville, we returned several times to do simulations. The school was a desirable location for several reasons. The well



at the school had a large amount of radon. The school had an aeration treatment system for the well water to decrease the amount of radon in their water. When we were there doing a simulation, the aeration treatment could be turned off so that our simulations could be done with the untreated water. The Swanville school provided a control situation where data could be taken with and without the treatment. The staff at the school was receptive to our presence there.

### 3.2 Measurement Procedure

A simulation consists of the following steps.

1. Honeywell\* Professional Radon Monitors are placed in the room where a simulation is to be done and in surrounding classrooms. Detectors are placed on countertops, desks or tables, a few feet above the floor. Detectors are left in place at least 1 hour before a simulation is done and up to 24 hours after the simulation is complete.
2. A Panametrics† Ultrasonic Acoustic flow meter is attached to the domestic water supply to monitor water use during the simulation.
3. The simulation is usually done in the kitchen where there are many water-use devices. Water is run through all possible devices for a period of 30-60 minutes.

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\*Sun Nuclear Corp., 425-A Pineada Ct., Melbourne, FL 32940, 321-259-6862

†Panametrics, 221 Crescent Street, Waltham, MA 02453, 800-833-9438

4. During the water-use period, 10 *ml* water samples are taken, using a syringe, from each appliance. The sample is injected under 5 *ml* of Packard's<sup>†</sup> High Efficiency Mineral Oil Scintillator in a 27 *ml* scintillation vial. To measure emissivity, a water sample is taken before and after the water is used by the appliance. Samples are taken periodically while the simulation is going since the radon concentration in the water can change during use. Samples are counted for radon in a Packard 1500<sup>§</sup> Liquid Scintillation Analyzer.
5. The ventilation rate of the room where the simulation takes place is determined using sulfur hexafluoride (SF<sub>6</sub>). The ventilation rate is how quickly the room ventilates, i.e., the number of air exchanges that a room has per unit time. Air samples are collected at timed intervals using an air pump and SKC<sup>¶</sup> 10 *l* mylar bags. The air is analyzed using Foxboro's<sup>||</sup> Miran Infrared gas analyzer. While the simulation is being done, the ventilation rate is measured in the room and, when possible, a classroom's ventilation rate is also measured.
6. Appliance water use is determined using a container of known volume and a stopwatch. The flow rate of the appliance is measured several times during the simulation. The average value of the flow rate is used to determine the water use of the appliance.
7. The volumes of rooms are measured and floor plans are obtained.

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<sup>†</sup>Packard Instrument Co., 800 Research Parkway, Meridan, CT 06450, 203-238-2351

<sup>§</sup>Packard Instrument Co., 800 Research Parkway, Meridan, CT 06450, 203-238-2351

<sup>¶</sup>SKC Inc., 334 Valley View Rd., Eighty Four, PA 05330

<sup>||</sup>Invensys/Foxboro, 33 Commercial Street, Foxboro, MA 02035, 866-746-6477

## 4 DATA AND RESULTS

Simulations were done at The University of Maine Darling Marine Center in Walpole, Maine, on 24 and 25 August 2000. Water samples, to be analyzed for  $^{222}\text{Rn}$ , were taken from four wells and a simulation conducted for three of the wells. The dormitory kitchen used water from Well # 6, which was found to have a  $^{222}\text{Rn}$  concentration of  $5500 \pm 100 \frac{\text{pCi}}{\ell}$ . The dimensions of the kitchen were measured and its volume was calculated to be  $6.95 \times 10^4 \pm 700 \ell$ . A simulation ran  $1050 \pm 10 \ell$  of water as measured by the flow meter. Two dish sprayers, one kitchen sink and one hand washing sink ran for 30 minutes. Using a 2.6  $\ell$  container and a stop watch, the flow rate of each appliance used in the simulation was measured. The flow rate determines the percentage of water used by each appliance and along with the emissivity for that particular appliance, a use-weighted emissivity is calculated for the simulation. The emissivity of the sprayer was measured on-site by taking water samples from the sprayer before and after its use. Average values for the emissivity taken from previous simulations were used in calculations for each of the two sink's emissivities. These data can be seen in Table 4.1.

The ventilation rate in the Darling Center dormitory kitchen was measured. Four 10  $\ell$  sample bags of air were taken at 15 minute intervals. The bags were then returned to The University of Maine and analyzed for  $SF_6$ . The natural log of the relative concentration of  $SF_6$  as a function of time is shown in Figure 4.1. The ventilation

Table 4.1: Use-weighted Emissivity for Darling Center Dorm Kitchen

Total Water Used: 1050 $\ell$ in 30 minutes				
Appliance	Flow Rate ( $\frac{\ell}{s}$ )	Ratio of Total Water Used	Emissivity of Appliance	Use-weighted Emissivity for Appliance
Sprayer #1	0.10	0.17	0.61	0.10
Sprayer #2	0.13	0.21	0.61	0.13
Sink #2	0.29	0.47	0.35	0.16
Hand Sink	0.10	0.15	0.31	0.05
<b>Total Use-weighted emissivity, <math>\bar{\epsilon}</math>, for the run:</b>				<b><math>0.44 \pm 0.02</math></b>

rate for the dormitory kitchen is found from the plot to be  $0.030 \pm 0.004 \frac{1}{min}$  using the method of least squares.

From equation 2.17, we can write the transfer coefficient as

$$f = \frac{W\bar{\epsilon}}{TV\lambda}. \quad (4.1)$$

Using this equation and the total amount of water used,  $W = 1050 \ell$ , the use-weighted emissivity for the simulation,  $\bar{\epsilon} = 0.44$ , the time elapsed during the simulation,  $T = 30min$ , the total volume of the room,  $V = 6.95 \times 10^4 \ell$ , and the ventilation rate for the room,  $\lambda = 0.030 \frac{1}{min}$ ,  $f$  is calculated to be  $7.5 \times 10^{-3} \pm 1.1 \times 10^{-3}$  for the dormitory kitchen.

Again, from equation 2.17, we have

$$f = \frac{\Delta C_{air}}{C_w}. \quad (4.2)$$

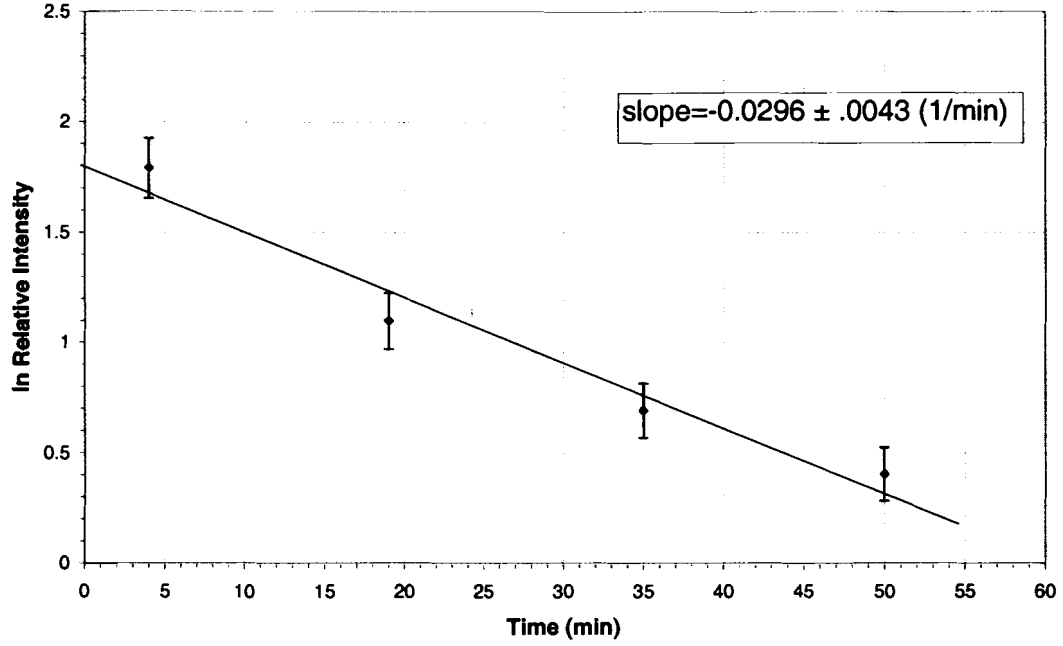


Figure 4.1: Ventilation Using  $SF_6$ , Darling Center Dorm Kitchen

In order to calculate  $f$  in this way, radon detectors were placed at three locations in the dormitory kitchen. Figure 4.2 shows a schematic drawing of the kitchen with the placement of the three detectors and the location of the water-use devices. The simulation in the kitchen was done from 13:35 to 14:05 and the detectors are left for another 18 hours to get a background value of  $^{222}\text{Rn}$ . The background value is used to calculate the *change* in concentration of radon in the air,  $\Delta C_{air}$ , that was released from the water during its use.

Figures 4.3, 4.5, and 4.4 show the data collected from the three detectors in the kitchen. A typical error bar is shown for one data point on each graph. A peak is seen on each of the detectors shortly after the simulation started. A maximum concentration is seen for each detector at 14:45 and a decrease to background by

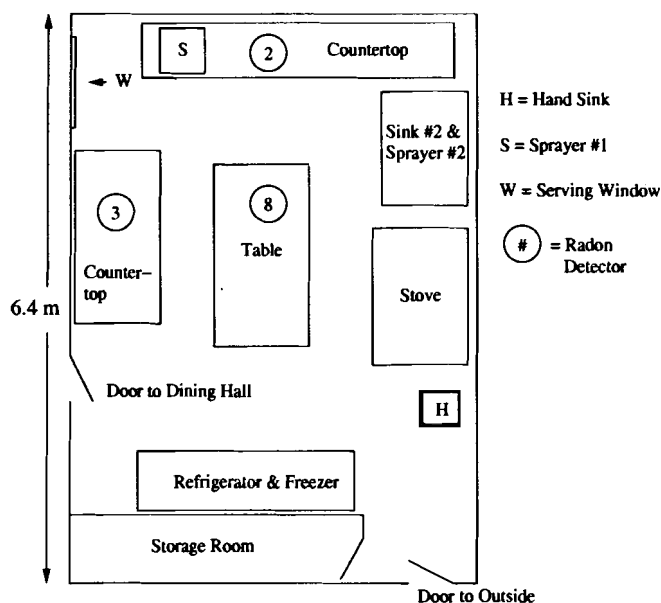


Figure 4.2: Schematic of the Darling Center Dorm Kitchen

17:45. Of the three detectors, #8, which was placed nearer to the middle of the room than the other two detectors, has the largest peak ( $9.3 \pm 0.1 \frac{pCi}{l}$ ) for radon levels. This may also be a consequence of detector #8 being positioned closer to sink #2 and sprayer #2, which used the greatest amount of water. Another peak can be seen early in the morning at 5:45 and 6:45 on detectors #2 and #3, respectively. These peaks can be attributed to a buildup of radon coming from the ground and building materials that occurs overnight when no one is there opening doors and windows. One reason this peak is more pronounced in detectors #2 and #3 could be because these two detectors were placed next to walls where radon from the ground and the building materials are likely to enter the room. The radon returns to background

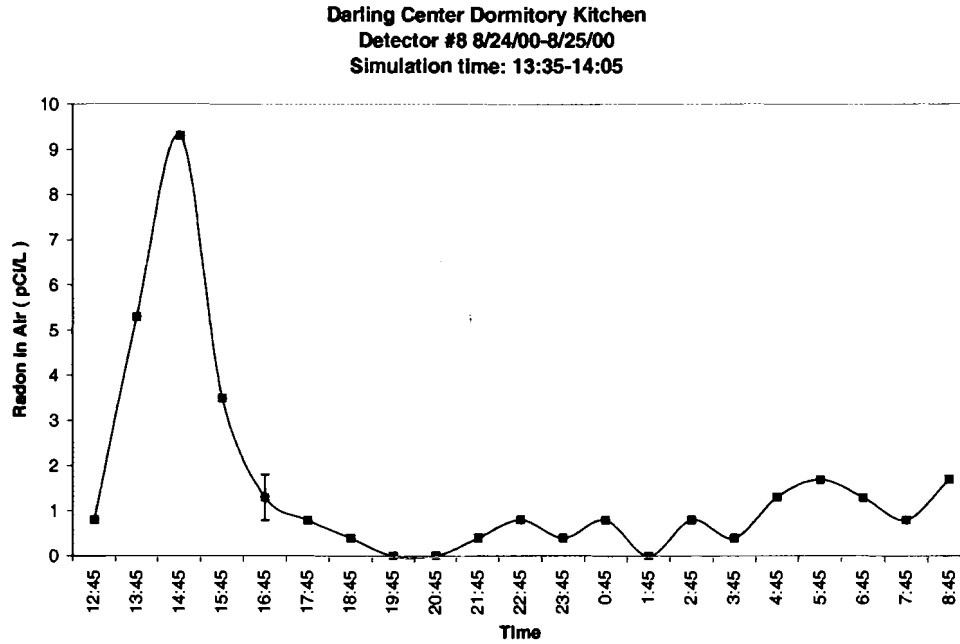


Figure 4.3: Darling Center Radon in Air, Detector #8

value after people enter the building by 9:00 in the morning and presumably open doors and windows.

Using detector #8 from 17:45 through 8:45 the next day, the average background value is  $0.8 \frac{pCi}{\ell}$ . And again from detector #8, the maximum value for the concentration of radon in the air during the simulation is  $9.3 \frac{pCi}{\ell}$ , giving  $\Delta C_{air} = 8.5 \frac{pCi}{\ell}$ . Using equation 4.2 and  $C_w = 5500 \frac{pCi}{\ell}$ , the transfer coefficient is calculated to be  $1.6 \times 10^{-3} \pm 2.4 \times 10^{-4}$ . This value for  $f$  is 129% smaller than the value calculated using equation 4.1.

We went to Swanville Nickerson School several times to perform simulations. Figures 4.7, 4.8, 4.9 and 4.10 show the radon in air measurements taken from four detectors placed in the kitchen and gym/cafeteria on 1 June 2001. A typical error bar is

Darling Center Dormitory Kitchen  
 Detector #2 8/24/00-8/25/00  
 Simulation time: 13:35-14:05

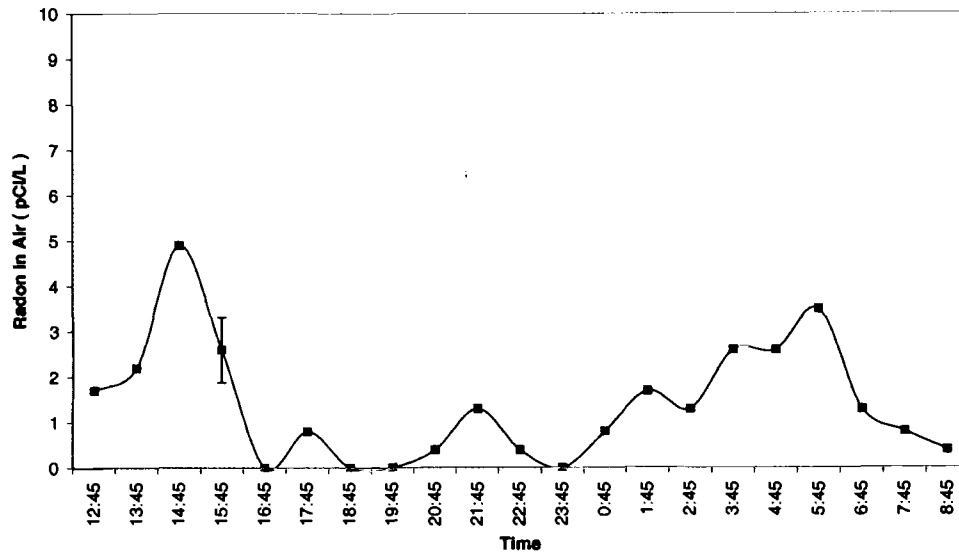


Figure 4.4: Darling Center Radon in Air, Detector #2

Darling Center Dormitory Kitchen  
 Detector #3 8/24/00-8/25/00  
 Simulation time: 13:35-14:05

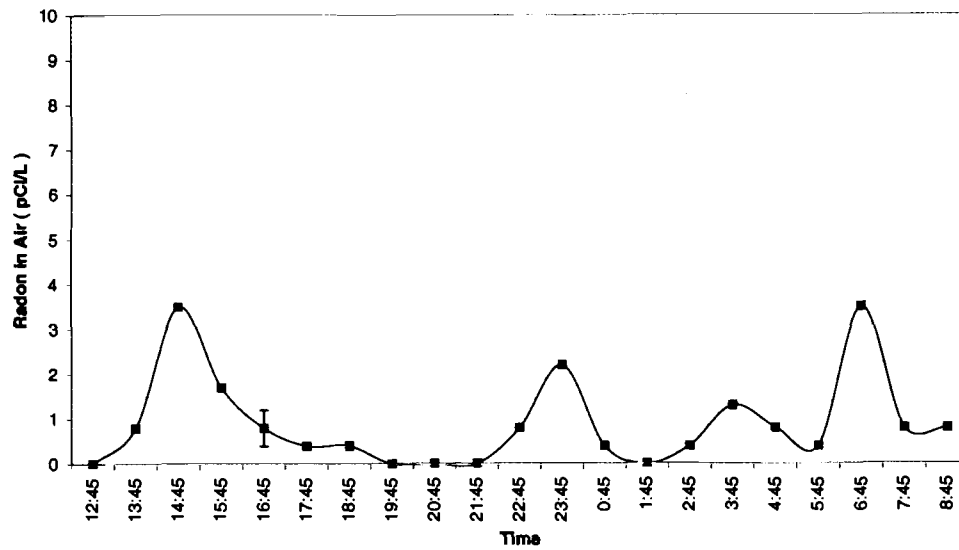


Figure 4.5: Darling Center Radon in Air, Detector #3



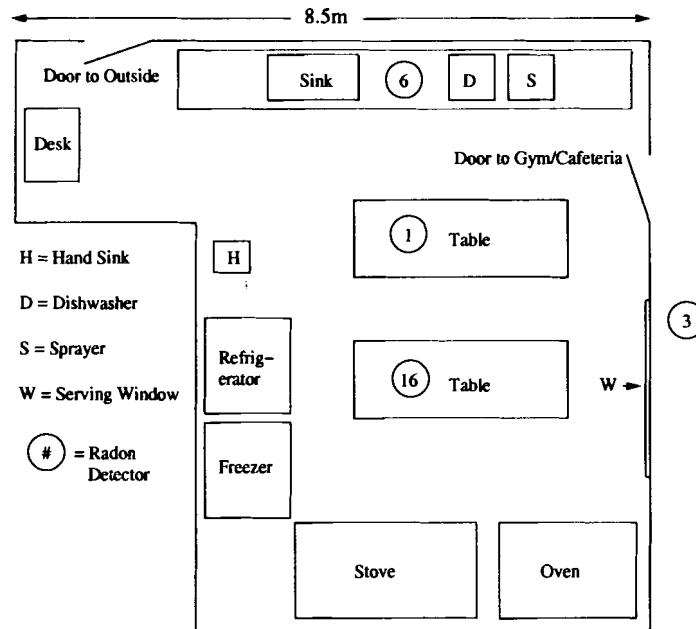


Figure 4.6: Schematic of the Swanville Kitchen

shown for one data point on each graph. The schematic of the Swanville kitchen can be seen in Figure 4.6. The four detectors were placed at varying distances away from the source, which was a kitchen sink and a sprayer. The first was placed between the two appliances about two feet away from each, the second was about four feet away and the third was around 12 feet away. The last detector was in the next room which was the gym/cafeteria and it was approximately 20 feet from the source. The radon levels decrease with distance from the source. Figure 4.11 is a plot of the maximum radon level from each detector,  $C_a$ , versus (approximate) distance from the source,  $r$ . The radon level decreases as  $\frac{1}{r^{1.2}}$ . As is seen in Figures 4.7, 4.8, 4.9 and 4.10 the four detectors experience peaks at nearly the same time and then each decay with time, suggesting that there is little mixing of the radon into the room.

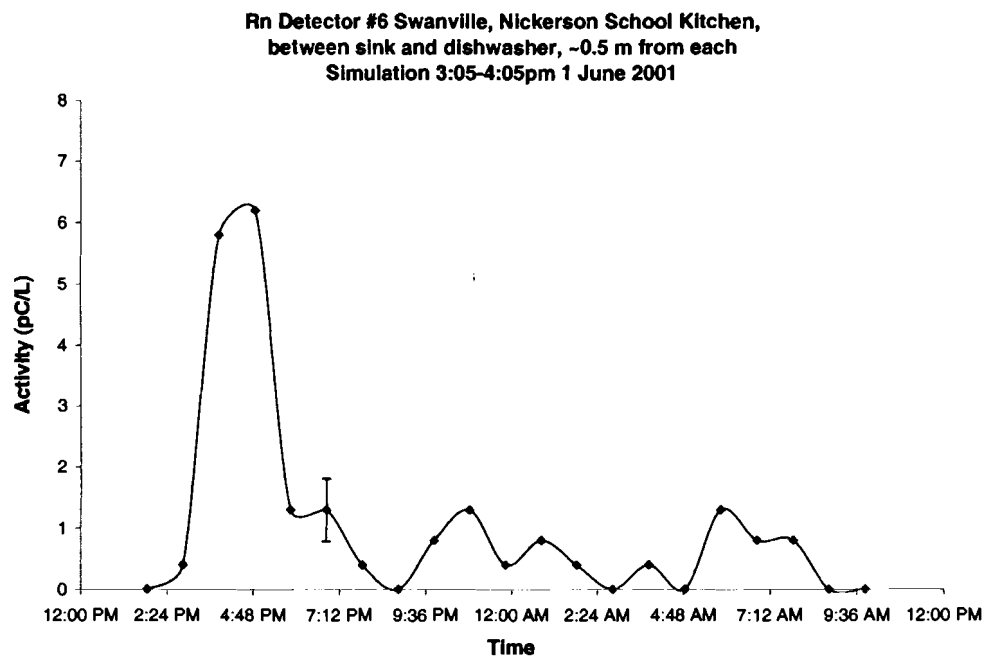


Figure 4.7: Swanville Radon in Air, Detector #6

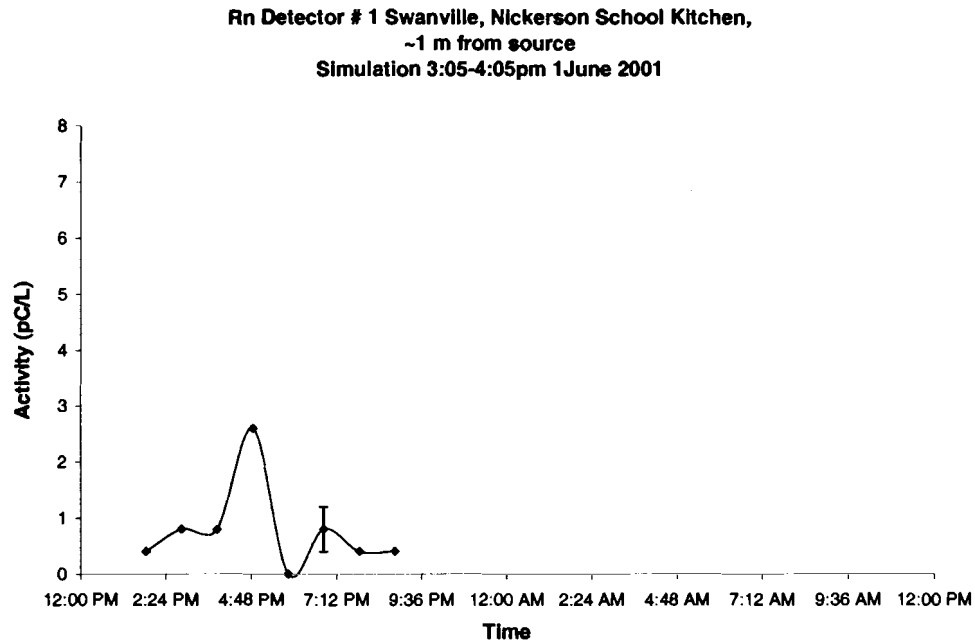


Figure 4.8: Swanville Radon in Air, Detector #1

**Rn Detector #16 Swanville, Nickerson School Kitchen,  
middle of room, ~3.5 m from each source  
Simulation 3:05-4:05pm 1 June 2001**

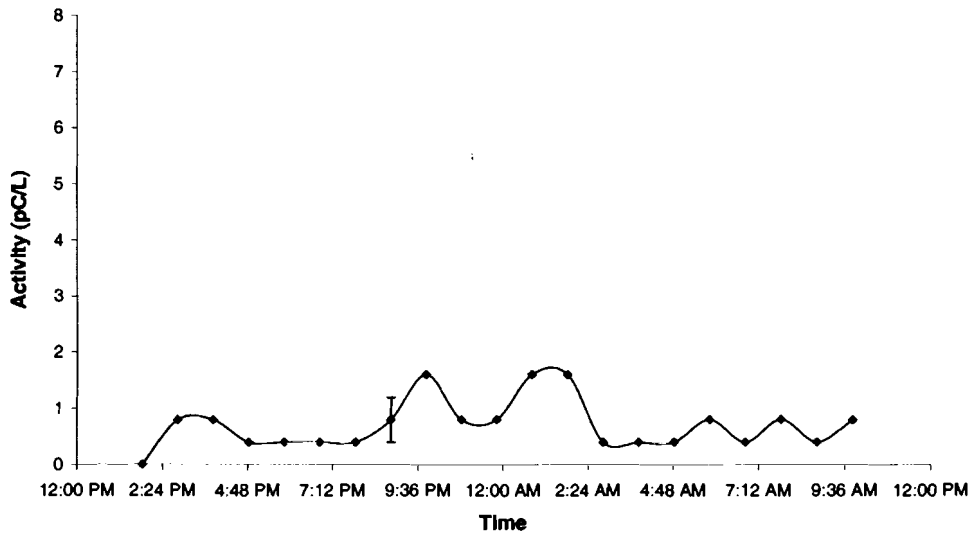


Figure 4.9: Swanville Radon in Air, Detector #16

**Rn Detector #3 Swanville, Nickerson School Gym  
~6 m from source  
Simulation 3:05-4:05pm 1 June 2001**

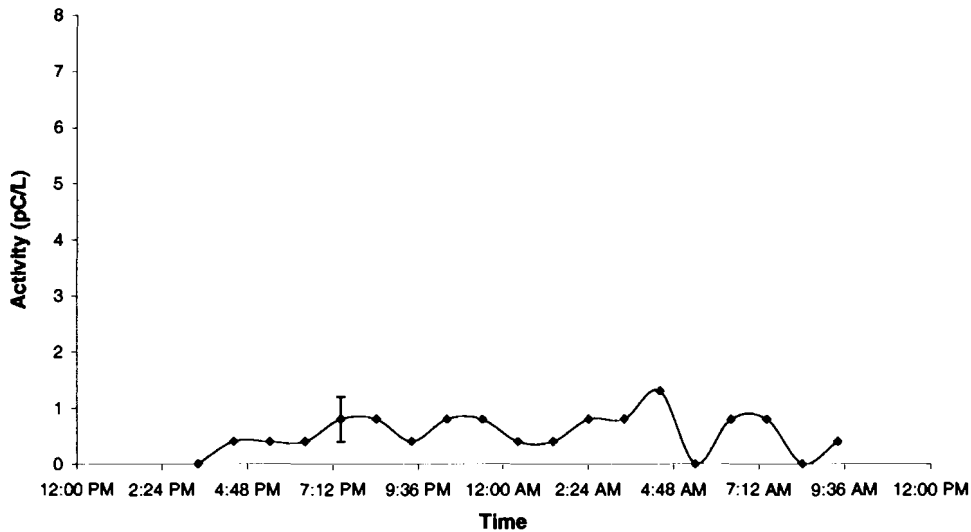


Figure 4.10: Swanville Radon in Air, Detector #3

Swanville School, Simulation 1June01  
Concentration of Radon in Air vs. Distance from Source

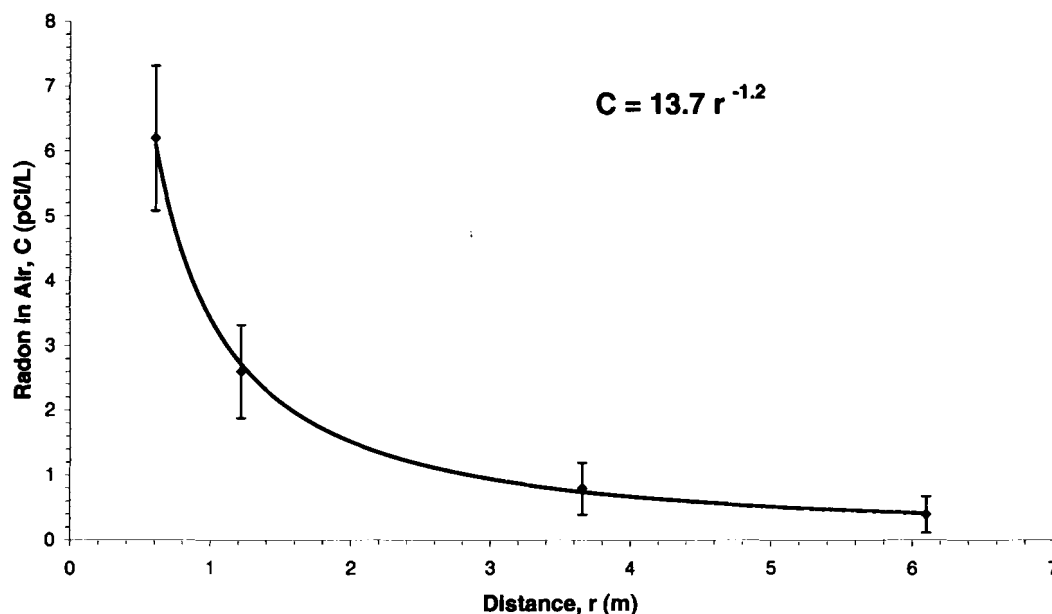


Figure 4.11: Concentration of Radon in Air vs. Distance

Simulations were done in selected kitchens and bathrooms for seven schools in Maine and at The University of Maine in Orono. The concentration of  $^{222}\text{Rn}$  in water found for these schools can be seen in Table 4.2. The values range from 260 to  $26,000 \frac{\text{pCi}}{\ell}$ . The Swanville Nickerson School has an aeration treatment system to decrease the amount of radon in the water. The system aerates the water by spraying it or mixing it with air, which allows the radon gas to escape from the water. Ventilation to the outside allows the radon to escape into outside air. Swanville's treated water had a concentration of radon of  $260 \frac{\text{pCi}}{\ell}$ . Without treatment, the concentration of  $^{222}\text{Rn}$  varies throughout the year. Water samples taken from the Nickerson School on 31 July 2000 gave the concentration of radon in water as  $24,000 \frac{\text{pCi}}{\ell}$ . In March

Table 4.2: Radon Concentrations in Water,  $C_w$

School	$C_w(\frac{pCi}{l})$
University of Maine, Bennett Hall	$270 \pm 10$
Dedham Elementary School	$3500 \pm 70$
Whitefield Elementary School	$880 \pm 30$
Brownville Elementary School	$4000 \pm 80$
Swanville Nickerson School (07/00)	$24000 \pm 480$
Swanville Nickerson School (aerated)	$260 \pm 10$
Swanville Nickerson School (03/01)	$12000 \pm 240$
Swanville Nickerson School (06/01)	$26000 \pm 520$
Darling Center Dorm Kitchen	$5700 \pm 110$
Darling Center Field Building	$26000 \pm 520$
Frankfort Elementary School	$560 \pm 20 -$ $2700 \pm 50$
Penobscot Consolidated School	$4600 \pm 100$

2001, the concentration was  $12,000 \frac{pCi}{l}$ . A third simulation performed in June 2001 had radon in water concentration at  $26,000 \frac{pCi}{l}$ .

The well at the Frankfort Elementary School had a varying concentration of radon in water over the time period of the simulation. During the 30 minute simulation, which used  $1100 \ell$  of water, the radon concentration changed from  $560$  to  $2700 \frac{pCi}{l}$ .

The emissivity of each appliance was measured while the simulation was performed. A compilation of the average values for emissivities found are in Table 4.3. The values range from  $0.04 \pm 0.001$  for a toilet to  $0.99 \pm 0.03$  for a dish washer. All appliances listed are from school kitchens and bathrooms. The dish sprayer is standard in most school kitchens and is used to rinse dishes prior to washing. Most of the dish washers were manufactured by Hobart and all were upright, rack type dish

Table 4.3: Measured Emissivities,  $\epsilon$

Appliance	Average Emissivity	Total number of appliances measured
Bathroom Sink	0.31	9
Hand Sink	0.41	7
Dish Sprayer	0.71	4
Dish Washer	0.99	2
Drinking Fountain	0.10	4
Kitchen Sink	0.35	6
Shower	0.59	2
Toilet	0.04	1
Urinal	0.17	1

washers, which have a pull-down hood. The kitchen sinks were all of a similar size and type in the schools tested, as were the hand sinks.

The ventilation rates taken in schools are listed in Table 4.4. The ventilation rate,  $\lambda$ , is the number of air changes a room experiences per unit time.  $\lambda$  is the quantity used in the calculation of the transfer coefficient. However, for ease of reading, the table also lists the quantity  $\frac{1}{\lambda}$ , which is the time it takes for the room to have one air change ventilation. The school and room where the ventilation rate was measured are listed in the table. The values for  $\lambda$  range from 0.012 to  $0.066 \frac{1}{min}$  and the values for  $\frac{1}{\lambda}$  range from 15 to 84 minutes.

Table 4.5 shows a list of transfer coefficients calculated using equation 4.1. For some of the schools, the data were not complete enough to calculate  $f$  in this manner. The values for  $f$  range from  $6.0 \times 10^{-4}$  to  $2.0 \times 10^{-2}$ . The values have a geometric

Table 4.4: Ventilation Rates,  $\lambda$ 

School and Room	$\lambda(\frac{1}{min})$	$\frac{1}{\lambda}(min)$
Bennett Hall, Room 11	$0.019 \pm 0.005$	53
Dedham Kitchen	$0.015 \pm 0.004$	67
Dedham Instructional Kitchen	$0.066 \pm 0.04$	15
Whitefield Kitchen	$0.023 \pm 0.003$	43
Whitefield Bathroom	$0.045 \pm 0.01$	22
Brownville Kitchen	$0.030 \pm 0.03$	33
Brownville Room 110	$0.051 \pm 0.01$	20
Frankfort Kitchen	$0.014 \pm 0.003$	70
Penobscot Kitchen	$0.012 \pm 0.001$	84
Swanville Boys Bathroom	$0.042 \pm 0.007$	24
Swanville Kitchen	$0.044 \pm 0.008$	23
Darling Center Dorm Kitchen	$0.030 \pm 0.004$	33
Darling Center Field Bathroom	$0.014 \pm 0.002$	70

mean of  $5.2 \times 10^{-3}$ . The three bathrooms have a geometric mean of  $2.8 \times 10^{-3}$ . For the seven kitchens, the geometric mean is  $7.0 \times 10^{-3}$ . In all cases, the transfer coefficient is for the room listed, using the volume of that room.

Table 4.6 contains values for the transfer coefficient calculated using equation 4.2. These values for  $f$  range from  $9.6 \times 10^{-6}$  to  $3.1 \times 10^{-3}$ . The values have a geometric mean of  $3.3 \times 10^{-4}$ . Some values are calculated for the same room using different detectors. Because of the variance of radon in the room, the value for  $\Delta C_{air}$  changes from detector to detector and the corresponding value of  $f$  changes as well. As seen in the table,  $f$  varies by an order of magnitude or more between detectors placed in the same room.

The values for  $f$  in Table 4.6 are on average 137% smaller than the corresponding value for  $f$  in Table 4.5. This difference must be attributed to the variation of radon in

Table 4.5: Transfer Coefficients,  $f$ , Calculated Using  $W, \bar{\epsilon}, V, T$ , and  $\lambda$

School	$f$
Bennett Hall, Room 11	$1.6 \times 10^{-2} \pm 4.3 \times 10^{-3}$
Dedham Instructional Kitchen	$7.0 \times 10^{-4} \pm 3.8 \times 10^{-4}$
Whitefield Kitchen	$8.2 \times 10^{-3} \pm 1.1 \times 10^{-3}$
Whitefield Bathroom	$1.8 \times 10^{-3} \pm 6.0 \times 10^{-4}$
Brownville Kitchen	$1.1 \times 10^{-2} \pm 9.4 \times 10^{-3}$
Frankfort Kitchen	$2.0 \times 10^{-2} \pm 4.2 \times 10^{-3}$
Swanville Boys Bathroom	$6.0 \times 10^{-4} \pm 9.5 \times 10^{-5}$
Swanville Kitchen	$4.3 \times 10^{-3} \pm 7.5 \times 10^{-4}$
Darling Center Dorm Kitchen	$7.5 \times 10^{-3} \pm 1.1 \times 10^{-3}$
Darling Center Field Bathroom	$2.0 \times 10^{-2} \pm 2.2 \times 10^{-3}$

the room.  $f$  is calculated using the concentration of radon in air,  $\Delta C_{air}$ , in Table 4.6. The radon detectors do not give an accurate value of the concentration of radon in the room because the value is dependent on *where* in the room the detector is placed. This results in a decreased value for the transfer coefficient, when it is calculated using  $\Delta C_{air}$ .

Graphs of the data from all seven schools can be found in Appendix A. A map of Maine with the locations of the schools in this study can be found in Appendix B. Also in Appendix B is a bedrock geologic map of Maine.



Table 4.6: Transfer Coefficients,  $f$ , Calculated Using  $\Delta C_{air}$  and  $C_w$

School	$f$
Dedham boys bathroom	$5.7 \times 10^{-4} \pm 1.8 \times 10^{-4}$
Dedham girls bathroom	$5.7 \times 10^{-4} \pm 1.8 \times 10^{-4}$
Dedham kitchen	$4.3 \times 10^{-4} \pm 1.6 \times 10^{-4}$
Whitefield kitchen	$2.8 \times 10^{-3} \pm 8.0 \times 10^{-4}$
Whitefield boys bathroom	$5.6 \times 10^{-4} \pm 3.6 \times 10^{-4}$
Swanville boys bathroom	$6.1 \times 10^{-5} \pm 2.2 \times 10^{-5}$
Swanville kitchen #3	$4.0 \times 10^{-4} \pm 5.7 \times 10^{-5}$
Swanville kitchen #8	$1.3 \times 10^{-3} \pm 1.1 \times 10^{-4}$
Swanville kitchen #2	$5.3 \times 10^{-4} \pm 6.7 \times 10^{-5}$
Swanville boys bath #15	$6.1 \times 10^{-5} \pm 2.2 \times 10^{-5}$
Swanville boys bath #12	$3.0 \times 10^{-5} \pm 1.6 \times 10^{-5}$
Penobscot girls locker #8	$1.0 \times 10^{-4} \pm 6.3 \times 10^{-5}$
Penobscot kitchen #7	$8.6 \times 10^{-4} \pm 1.9 \times 10^{-4}$
Penobscot kitchen #11	$4.3 \times 10^{-4} \pm 1.4 \times 10^{-4}$
Penobscot kitchen #16	$2.1 \times 10^{-3} \pm 3.0 \times 10^{-4}$
Penobscot kitchen #12	$6.5 \times 10^{-4} \pm 1.7 \times 10^{-4}$
Penobscot girls locker #2	$4.3 \times 10^{-4} \pm 1.4 \times 10^{-4}$
Frankfort boys bath #7	$7.3 \times 10^{-4} \pm 2.3 \times 10^{-4}$
Frankfort kitchen #3	$3.6 \times 10^{-4} \pm 1.6 \times 10^{-4}$
Frankfort kitchen #2	$4.7 \times 10^{-4} \pm 1.8 \times 10^{-4}$
Swanville kitchen #6	$2.3 \times 10^{-4} \pm 4.2 \times 10^{-5}$
Swanville kitchen #1	$7.6 \times 10^{-5} \pm 2.4 \times 10^{-5}$
Swanville kitchen #16	$1.9 \times 10^{-5} \pm 1.2 \times 10^{-5}$
Swanville Gym #3	$9.6 \times 10^{-6} \pm 8.6 \times 10^{-6}$
Darling Center dorm kitchen	$1.6 \times 10^{-3} \pm 2.4 \times 10^{-4}$
Darling Center field bath	$3.1 \times 10^{-3} \pm 1.7 \times 10^{-4}$

## 5 SUMMARY AND CONCLUSIONS

The seven schools measured in this study had radon concentrations ranging from  $270 \pm 10$  to  $26,000 \pm 520 \frac{pCi}{\ell}$ . Toilets have the lowest emissivities of 0.04 and dish sprayers and dish washers have the highest emissivities of 0.71 and 0.99, respectively. The calculated values for water use-weighted emissivities ranged from 0.26-0.44 for the simulations performed. The values for  $f$  calculated using equation 4.1 range from  $6.0 \times 10^{-4}$  to  $2.0 \times 10^{-2}$ . The values have a geometric mean of  $5.2 \times 10^{-3}$ . The three bathrooms have a geometric mean of  $2.8 \times 10^{-3}$ . For the seven kitchens, the geometric mean is  $7.0 \times 10^{-3}$ . These values were calculated using the appropriate volume of the kitchen or the bath. The values for the transfer coefficient calculated using equation 4.2 range from  $9.6 \times 10^{-6}$  to  $3.1 \times 10^{-3}$ . The values have a geometric mean of  $3.3 \times 10^{-4}$ .

The concentration of radon in water was found to vary in two different cases. The concentration of radon in the Swanville Nickerson School's well seemed to vary by time of year. Measurements of the radon concentration for this well had values of  $24,000 \frac{pCi}{\ell}$ ,  $12,000 \frac{pCi}{\ell}$ , and  $26,000 \frac{pCi}{\ell}$  in July 2000, March 2001 and June 2001, respectively. During a simulation at the Frankfort Elementary School, the concentration of radon in the water increased as water was being used. Measurements of the radon in water were made several times during the simulation which used 1100  $\ell$  of water. The concentration of radon in the water varied from 560 to  $2700 \frac{pCi}{\ell}$  over the course of the 30 minute simulation.

By placing numerous radon in air detectors in a single room, it was determined that the radon gas does not homogeneously mix with the room air. This leads to a discrepancy in the values calculated for the transfer coefficient. On average, the value for  $f$  found using equation 4.2 was 137% less than the value calculated using equation 4.1 for seven values that can be compared using the two methods. Equation 4.1 uses the total water used, emissivity, volume of the room or building, and the ventilation rate, whereas equation 4.2 uses only the change of concentration of radon in the air and the concentration of radon in the water. This discrepancy may be due to insufficiently assessing the amount of radon in the room by placing too few detectors. Future work should include modeling of the diffusion of radon into a room and into the rest of the building.

Further investigation and modeling of the transfer coefficient is needed. The large range of values found for  $f$  suggest that it is not a constant, but may have a functional dependence on one or more of the variables that describe it. For instance, in the mass flow theory, the emissivity of an appliance,  $\varepsilon$ , is treated as a constant for each appliance. However, the amount of radon that an appliance emits is dependent on conditions such as humidity, temperature and pressure, which this theory does not account for.

## REFERENCES

- [1] Merril Eisenbud and Thomas Gesell. *Environmental Radioactivity From Natural, Industrial, and Military Sources*. Academic Press, fourth edition, 1997.
- [2] C.T. Hess, C.V. Weiffenbach, and S.A. Norton. Variations of airborne and waterborne  $\text{rn-222}$  in houses in Maine. *Environment International*, 8:59–66, 1982.
- [3] P.K. Hopke, T.B. Borak, J. Doull, J.E. Cleaver, K. F. Eckerman, L.C.S. Gundersen, N.H. Harley, C.T. Hess, N.E. Kinner, K.J. Kopecky, T.E. McKone, R.G. Sextro, and S.L. Simon. The health risks due to radon in drinking water. *Environmental Science and Technology*, 34(6):921–926, 2000.
- [4] L.E. Welch and D.M. Mossman. An environmental chemistry experiment: The determination of radon levels in water. *Journal of Chemical Education*, 71(6):521–523, June 1994.
- [5] United States Environmental Protection Agency Communications, Education, and Media Relations (1703). EPA proposes new standards to protect public health from radon in drinking water and indoor air, October 1999. Press Release. <http://www.epa.gov/iaq/radon/waterpres.html>.
- [6] C.T. Hess and L.E. Haskell. *Water Contamination and Health: Integration of Exposure Assessment, Toxicology, and Risk Assessment*. Marcel Dekker, Inc., 1994.
- [7] E.B. LaChapelle. A study of radon-222 from potable water sources to household air. Master's thesis, University of Maine, Orono, 1988.
- [8] L. Grodzins, H.E. Warren, and E.G. Room. The state of maine school radon project protocols and procedures. In *EPA 1991 International Symposium on Radon Reduction Technology*, Philadelphia, PA, April 2-5 1991.
- [9] George P. Bernhardt IV and C.T. Hess. Acute exposure from  $^{222}\text{Rn}$  and aerosols in drinking water. *Environment International*, 22:S753–S759, 1996.
- [10] A.J. Siniscalchi, S.J. Tibbetts, X. Soto, R.C. Beakes, K. van der Leeden, M.A. Thomas, and N.W. McHone. Implications of temporal variations in radon exposures in schools. *Environment International*, 22:S1015–S1024, 1996.
- [11] C.T. Hess, M.A. Vietti, and D.T. Mage. Radon from drinking water. In *Trace Substances in Environmental Health-XXI*. D.D. Hemphill, Ed., University of Missouri, Columbia, 1987.

## APPENDIX A: COMPLETE SET OF FIGURES

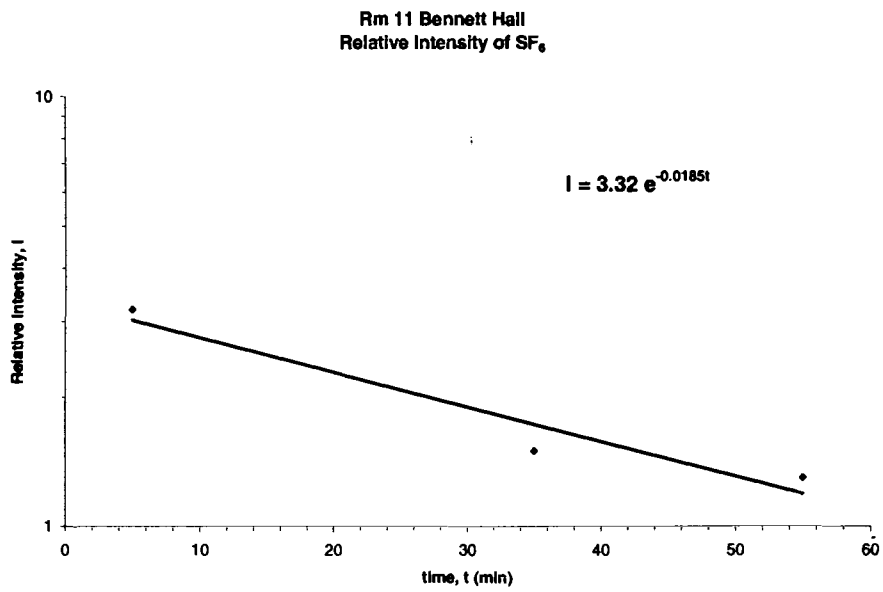


Figure A.1: Bennett Hall Ventilation

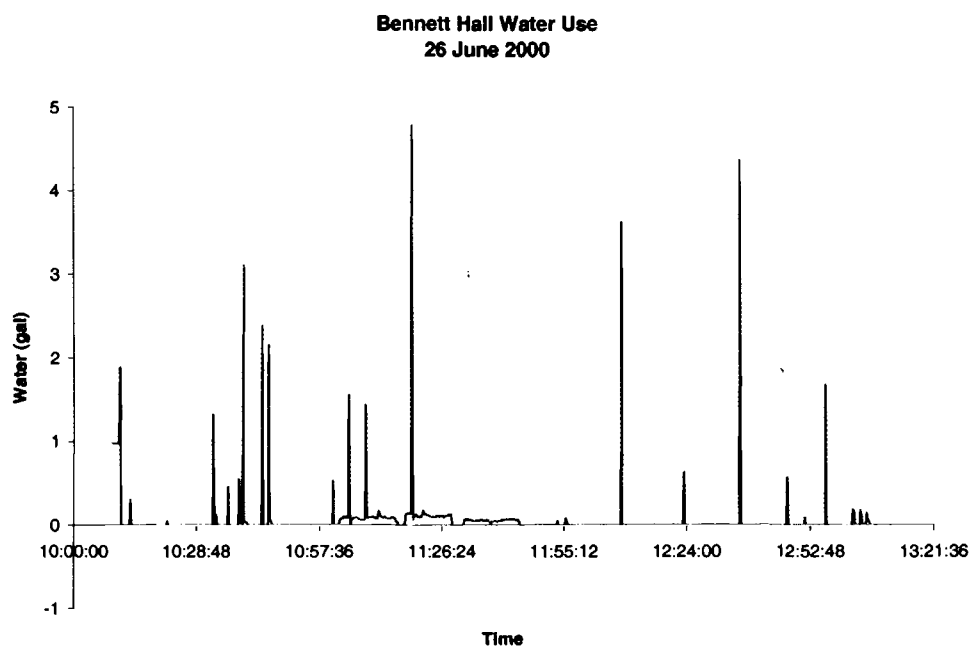


Figure A.2: Bennett Hall Water Use

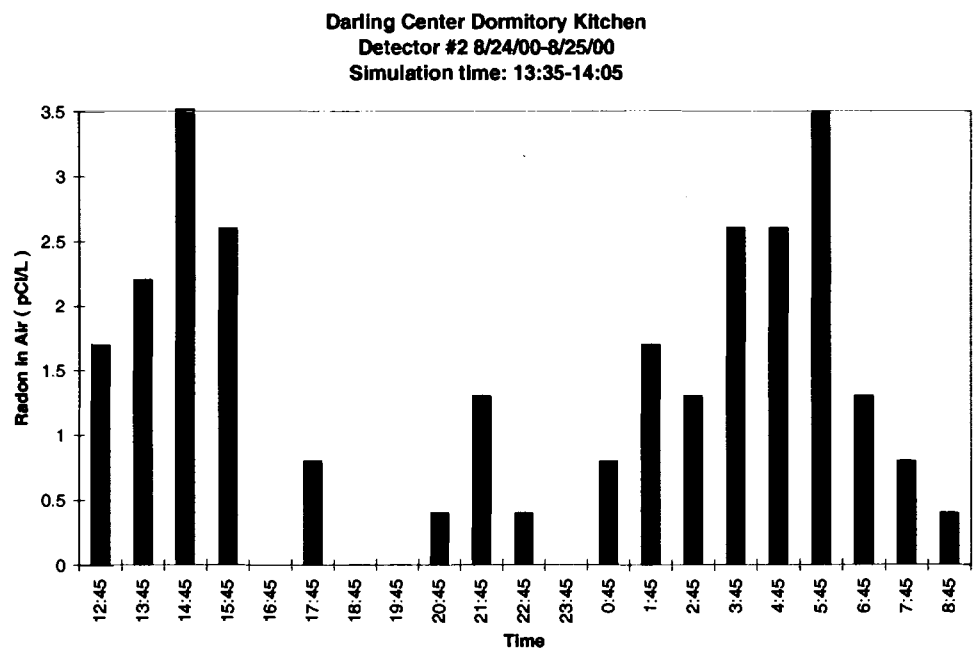


Figure A.3: Darling Center Radon in Air, 1

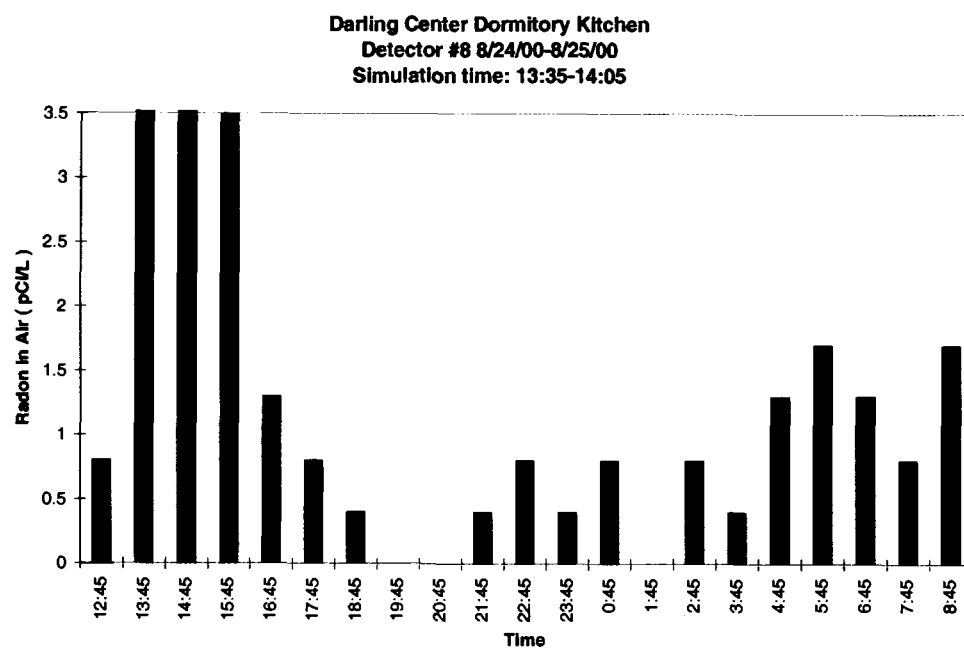


Figure A.4: Darling Center Radon in Air, 2

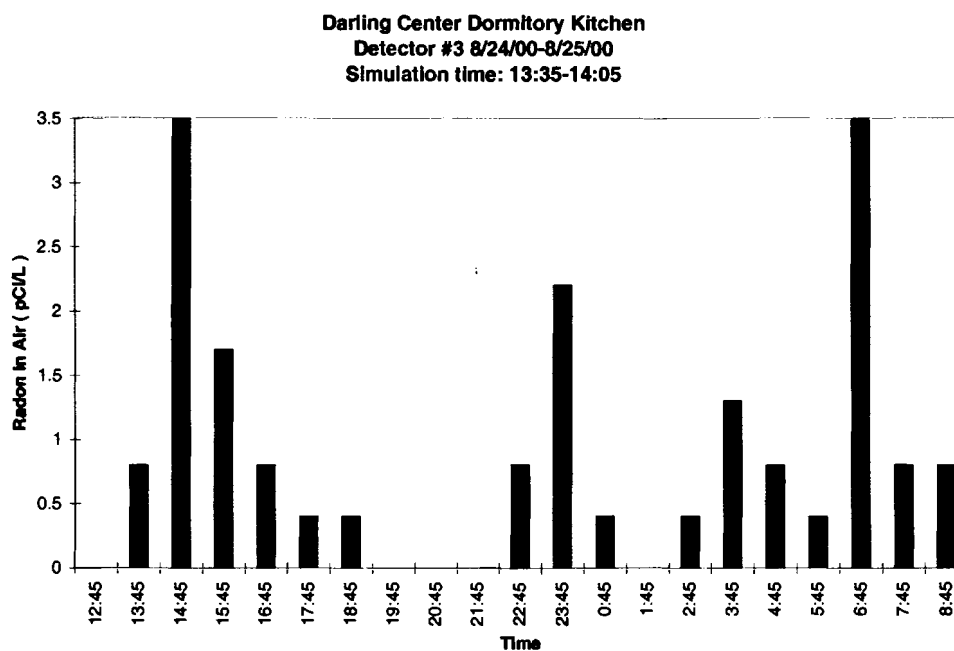


Figure A.5: Darling Center Radon in Air, 3

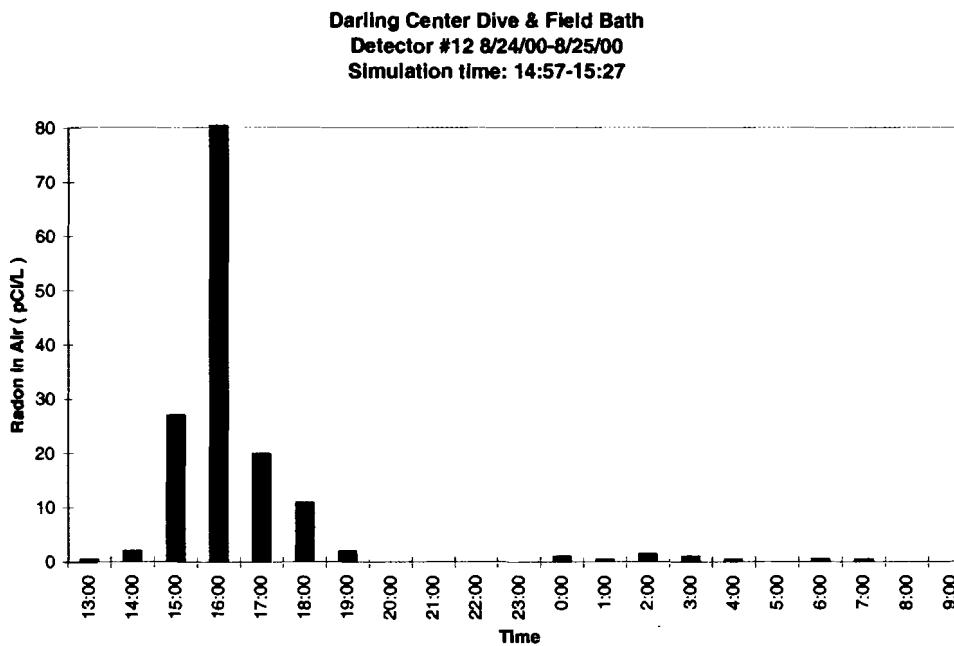
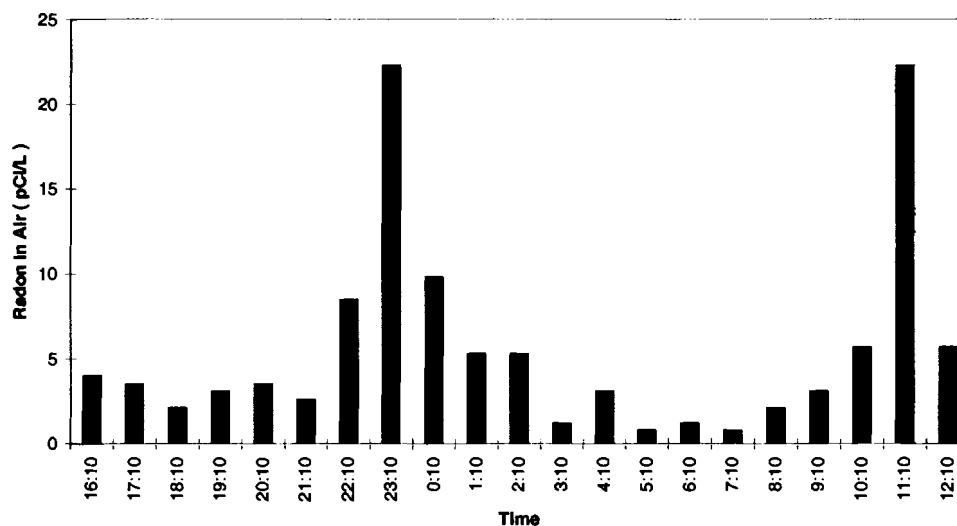


Figure A.6: Darling Center Radon in Air, 4



[illegible]

**Darling Center Flowing Seawater Lab Bath**  
**Detector #7 8/24/00-8/25/00**  
**Simulation time: 10:37-11:07**



38

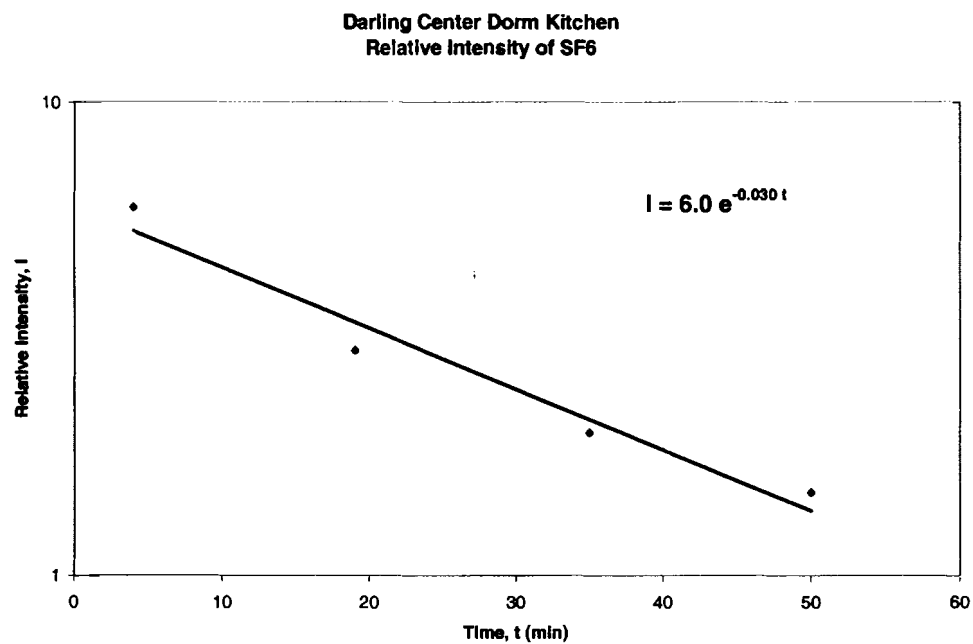


Figure A.9: Darling Center Ventilation, 1

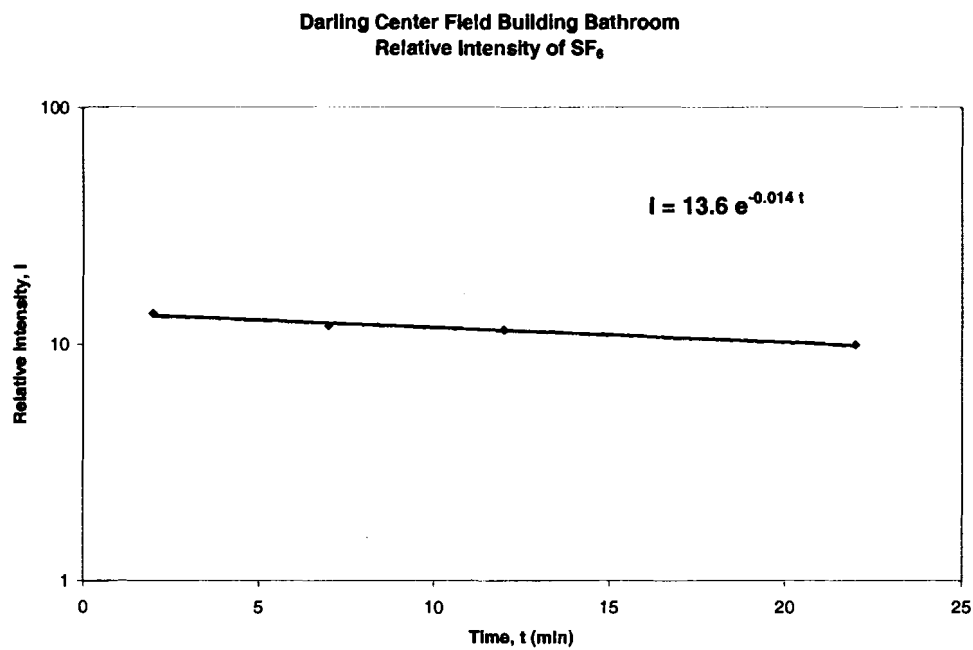


Figure A.10: Darling Center Ventilation, 2

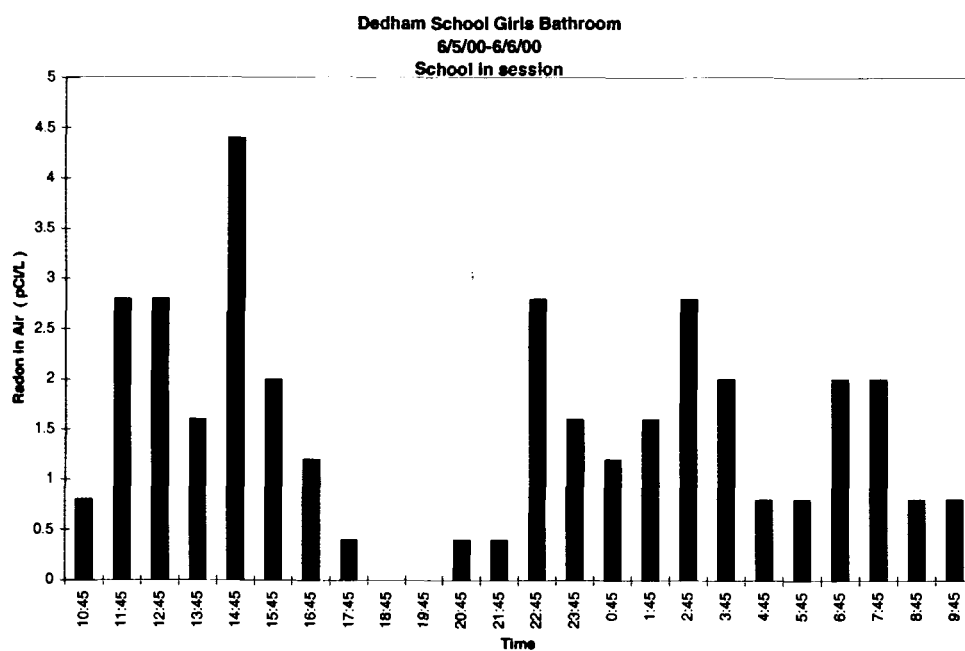


Figure A.11: Dedham Radon in Air, 1

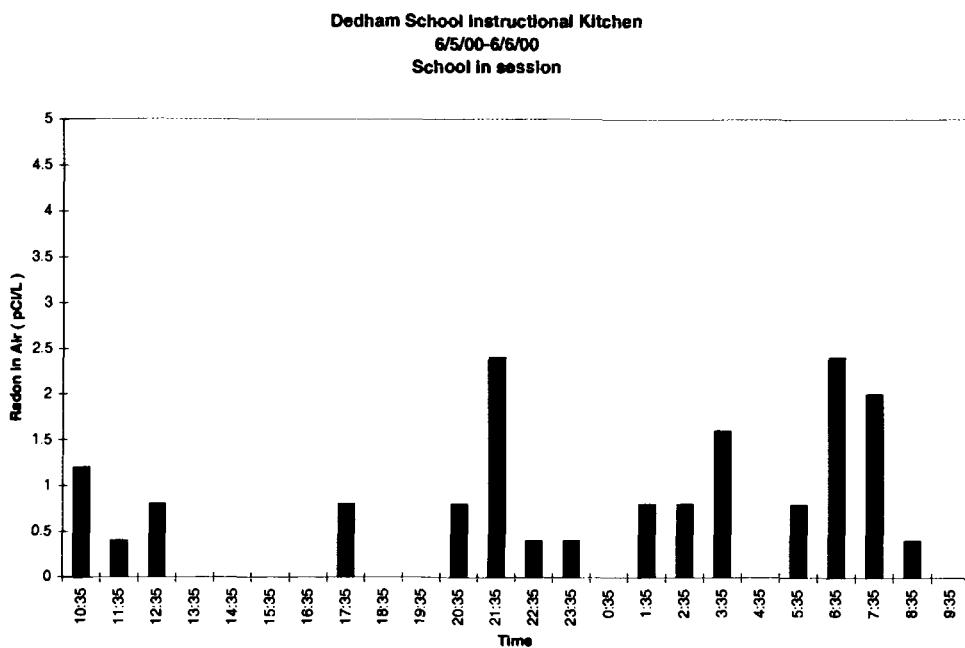


Figure A.12: Dedham Radon in Air, 2

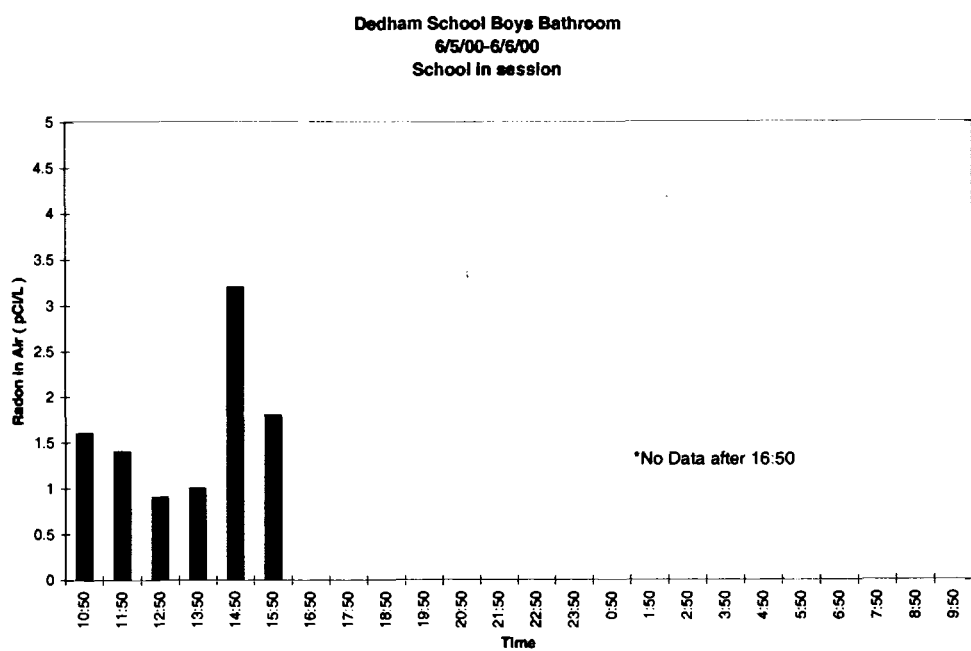


Figure A.13: Dedham Radon in Air, 3

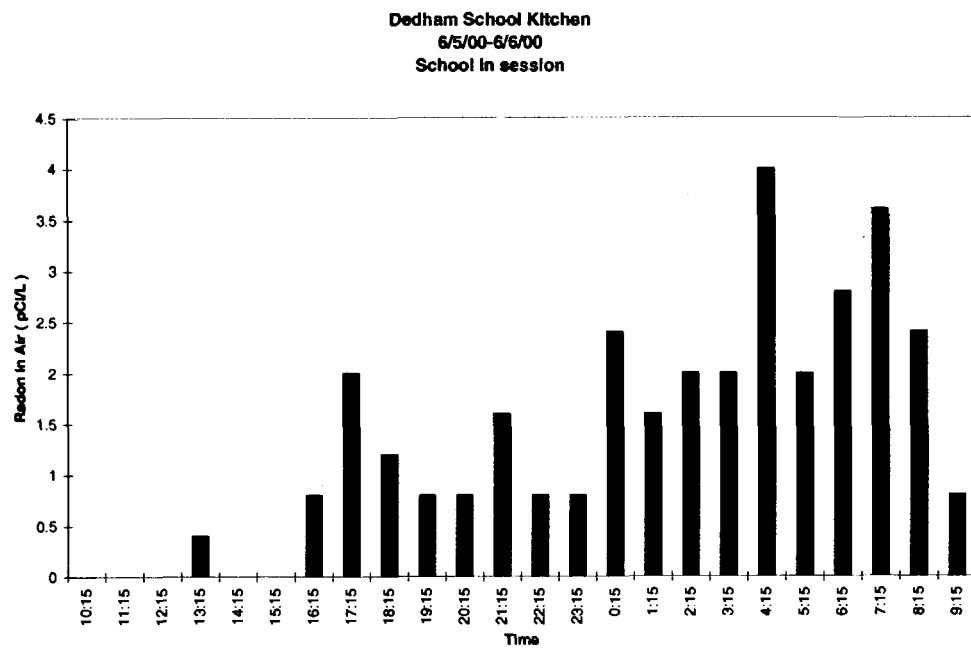


Figure A.14: Dedham Radon in Air, 4

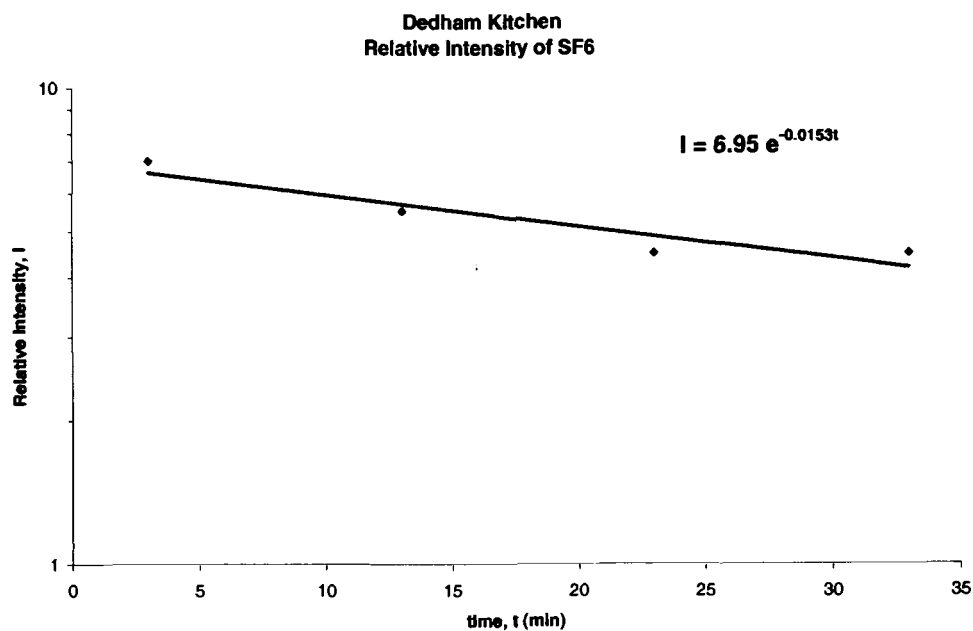


Figure A.15: Dedham Ventilation, 1

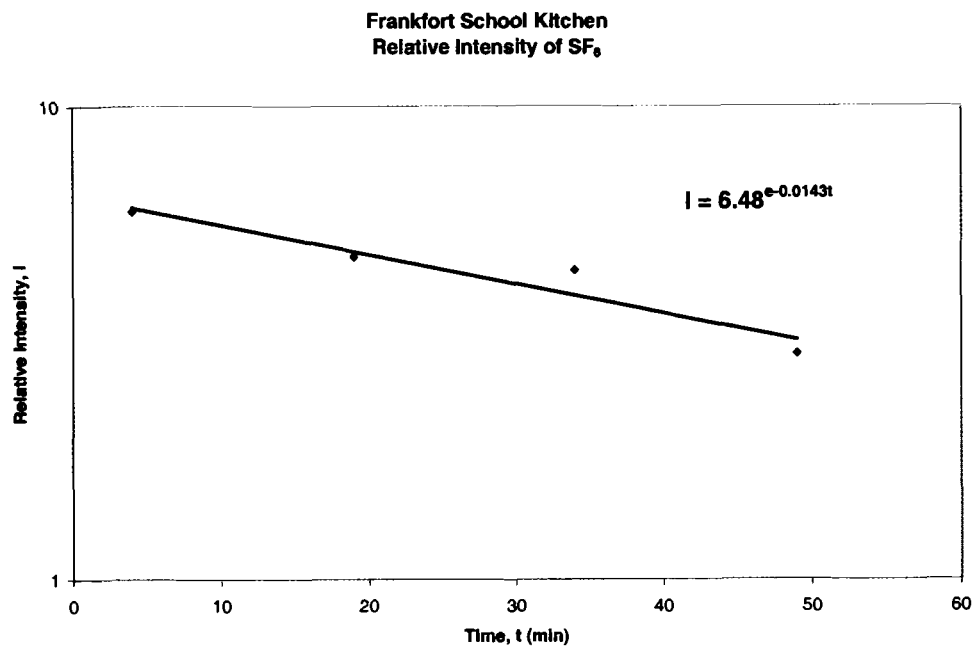


Figure A.16: Frankfort Ventilation

Penobscot Elementary Kitchen  
 Detector #12 8/21/00-8/22/00  
 Simulation time: 11:00-11:30 (8/21/00)

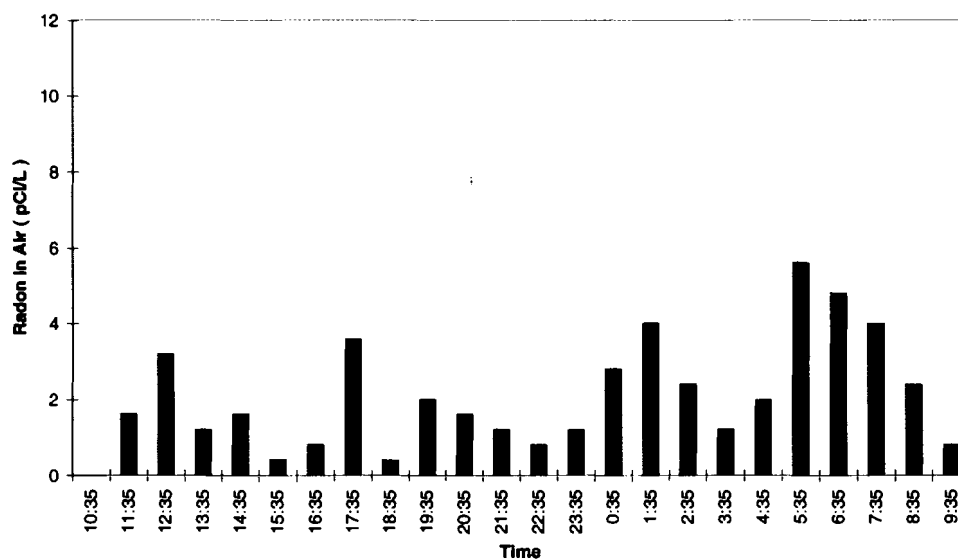


Figure A.17: Penobscot Radon in Air, 1

Penobscot Elementary Kitchen  
 Detector #16 8/21/00-8/22/00  
 Simulation time: 11:00-11:30 (8/21/00)

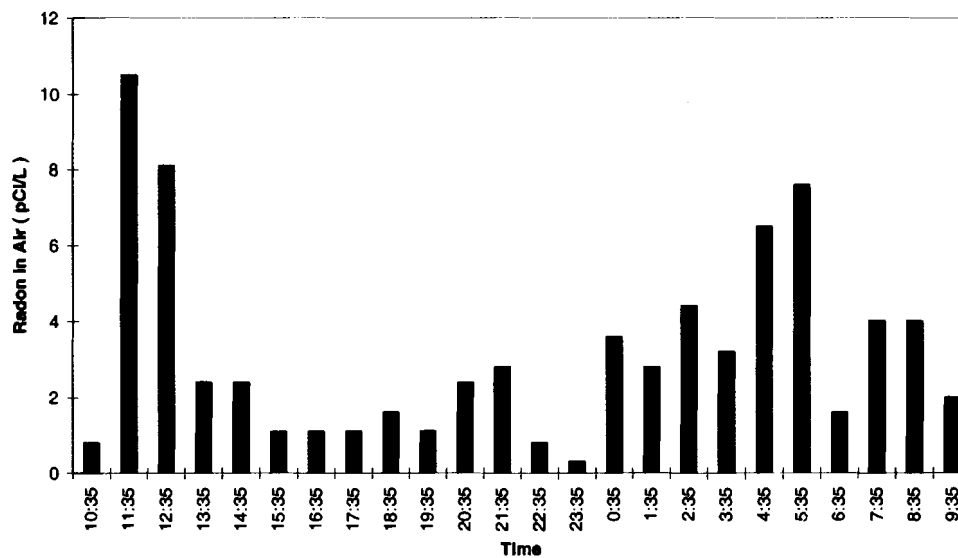


Figure A.18: Penobscot Radon in Air, 2

Penobscot Elementary Kitchen  
 Detector #11 8/21/00-8/22/00  
 Simulation time: 11:00-11:30 (8/21/00)

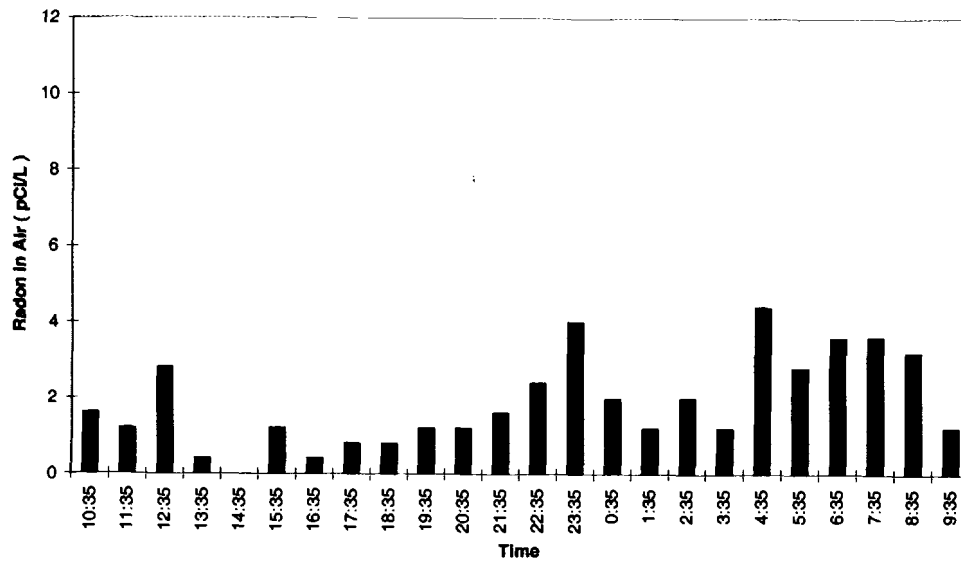


Figure A.19: Penobscot Radon in Air, 3

Penobscot Elementary Kitchen  
 Detector #7 8/21/00-8/22/00  
 Simulation time: 11:00-11:30 (8/21/00)

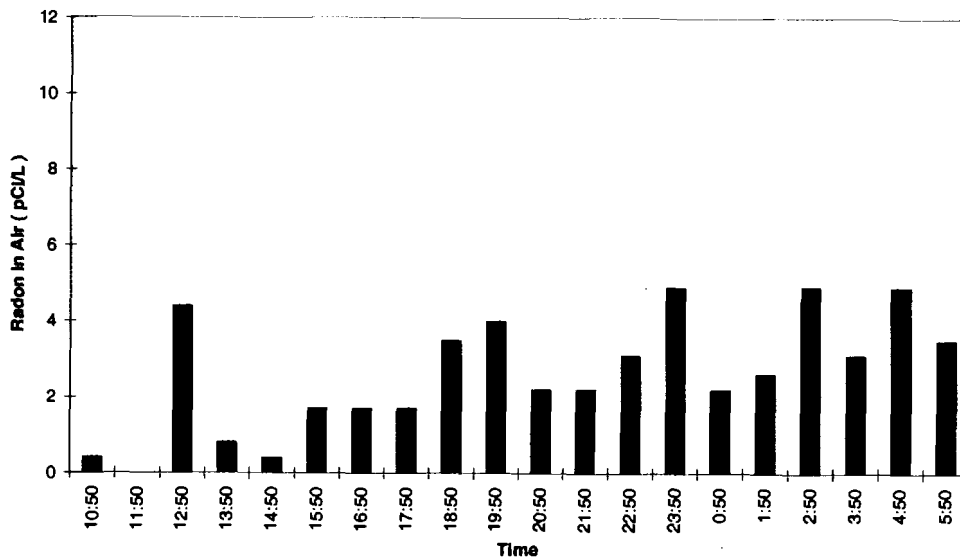


Figure A.20: Penobscot Radon in Air, 4

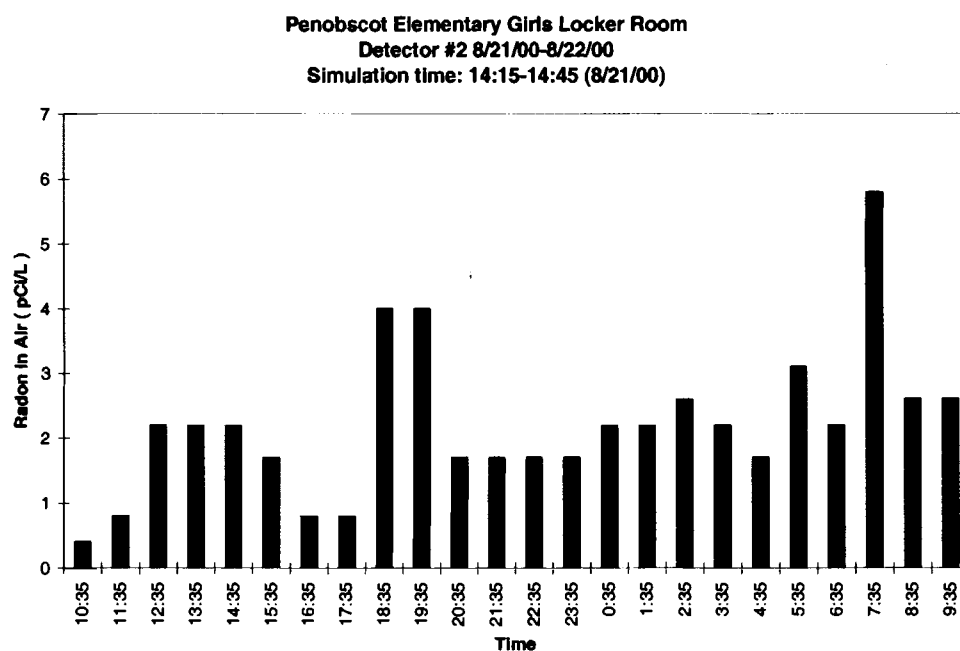


Figure A.21: Penobscot Radon in Air, 5

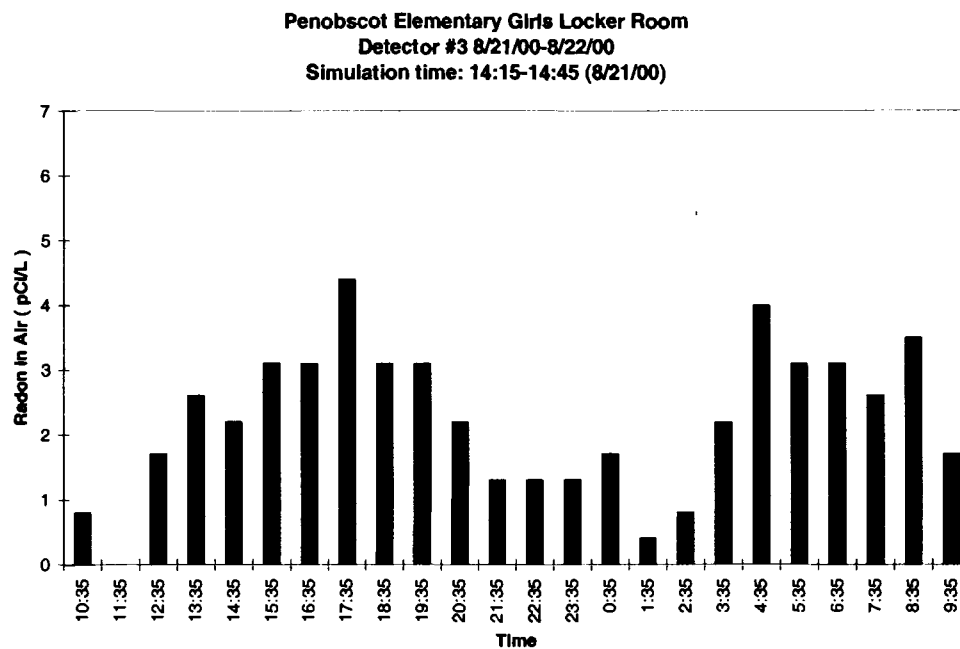


Figure A.22: Penobscot Radon in Air, 6



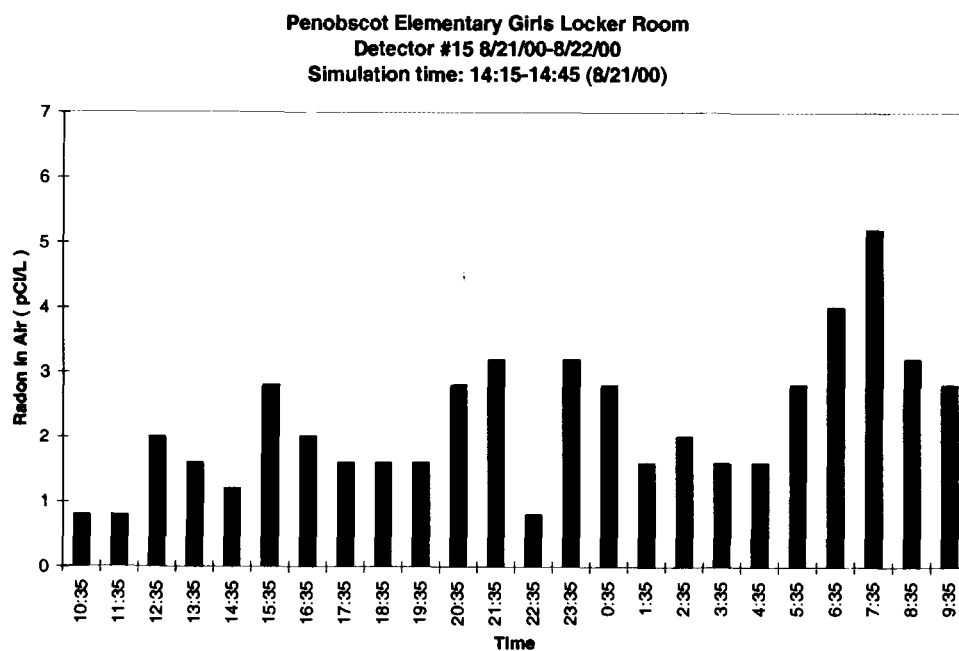


Figure A.23: Penobscot Radon in Air, 7

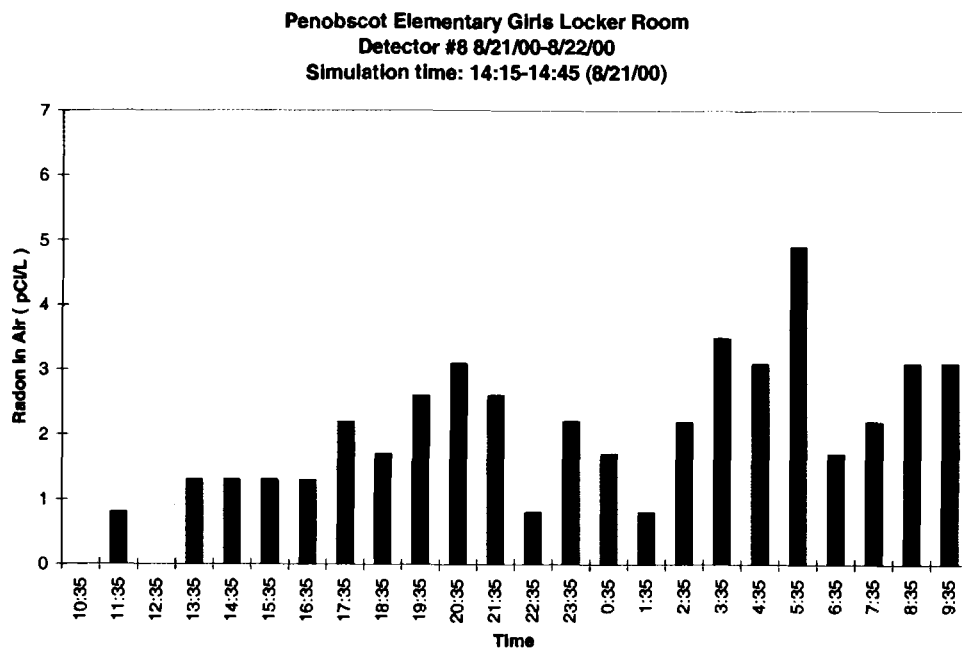


Figure A.24: Penobscot Radon in Air, 8

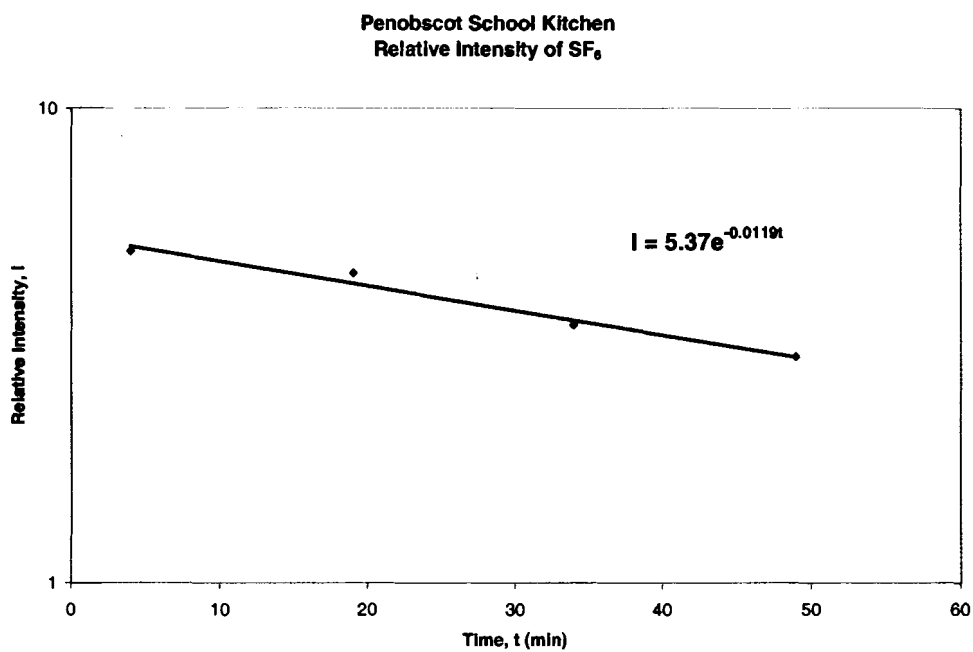


Figure A.25: Penobscot Ventilation, 1

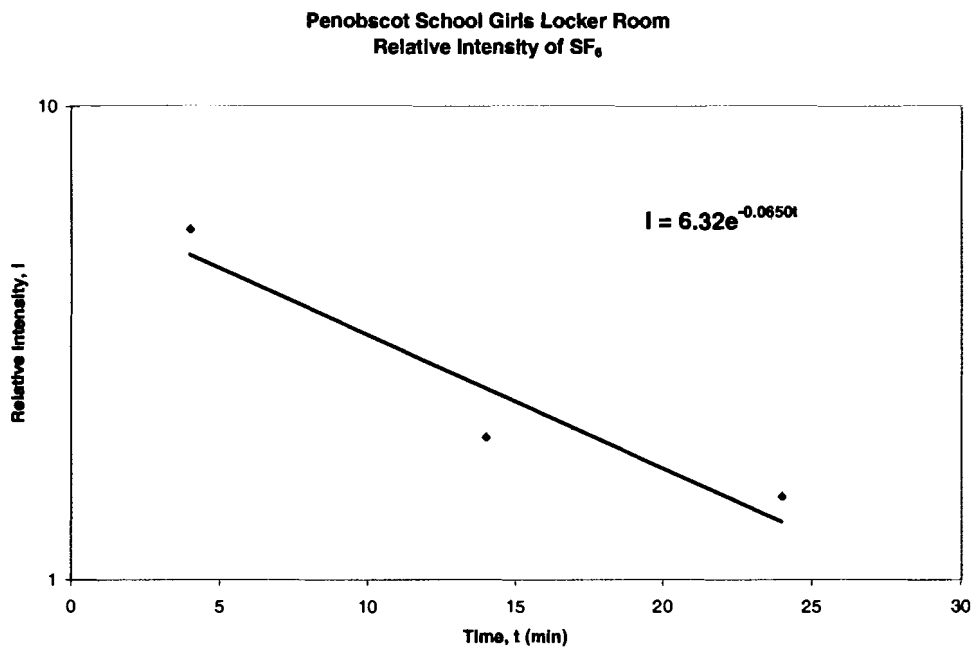


Figure A.26: Penobscot Ventilation, 2

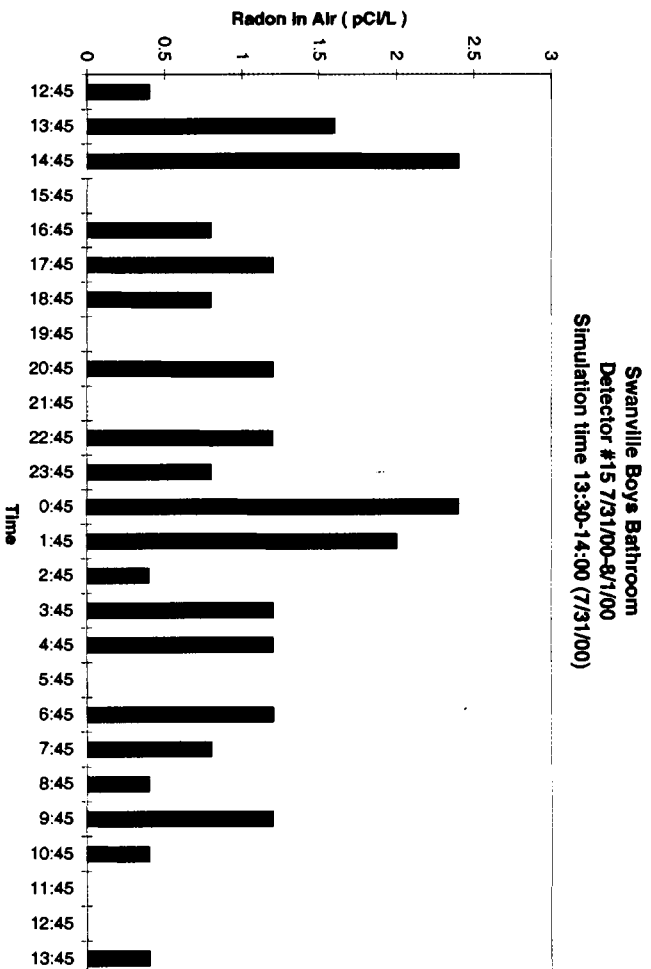


Figure A.27: Swanville Radon in Air, 4

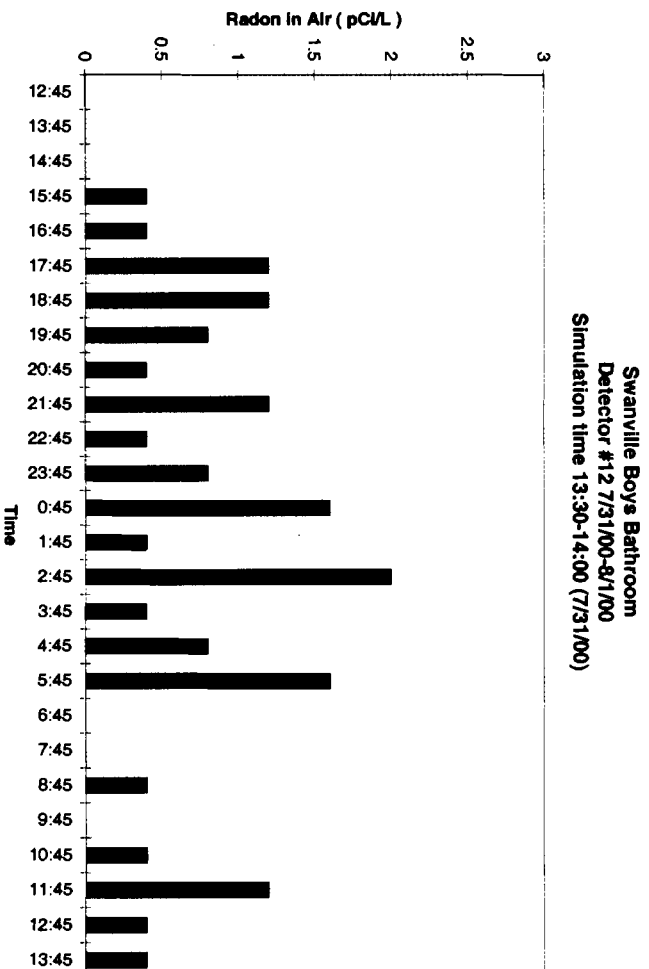


Figure A.28: Swanville Radon in Air, 5

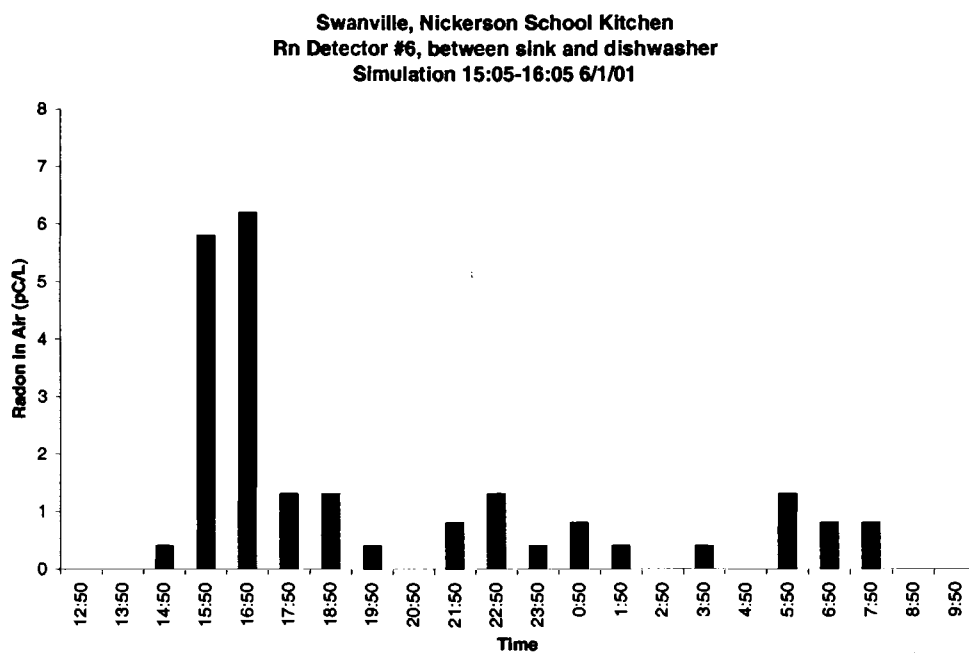


Figure A.29: Swanville Radon in Air, 6

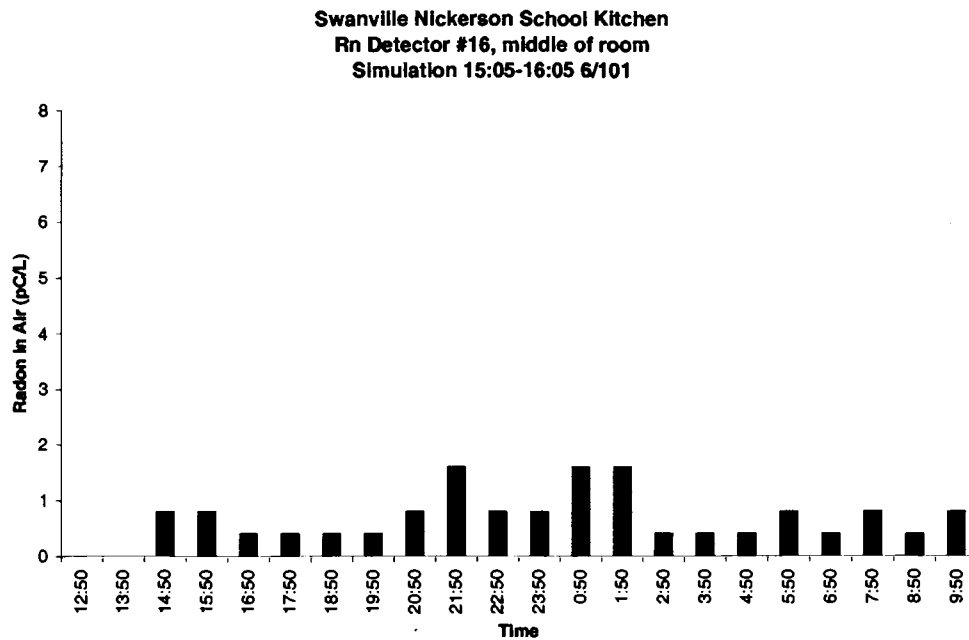


Figure A.30: Swanville Radon in Air, 7

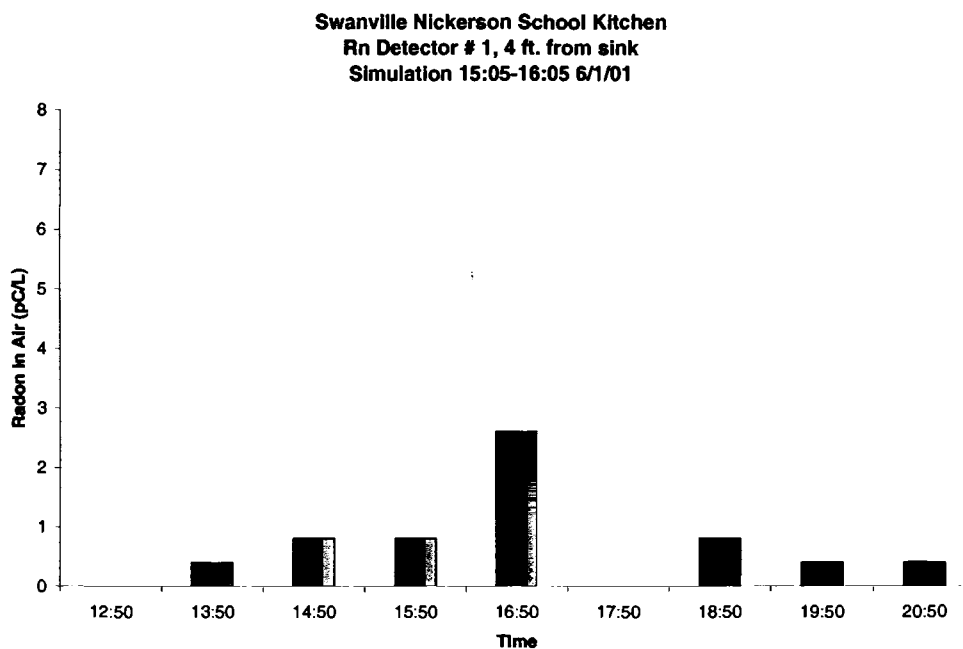


Figure A.31: Swanville Radon in Air, 8

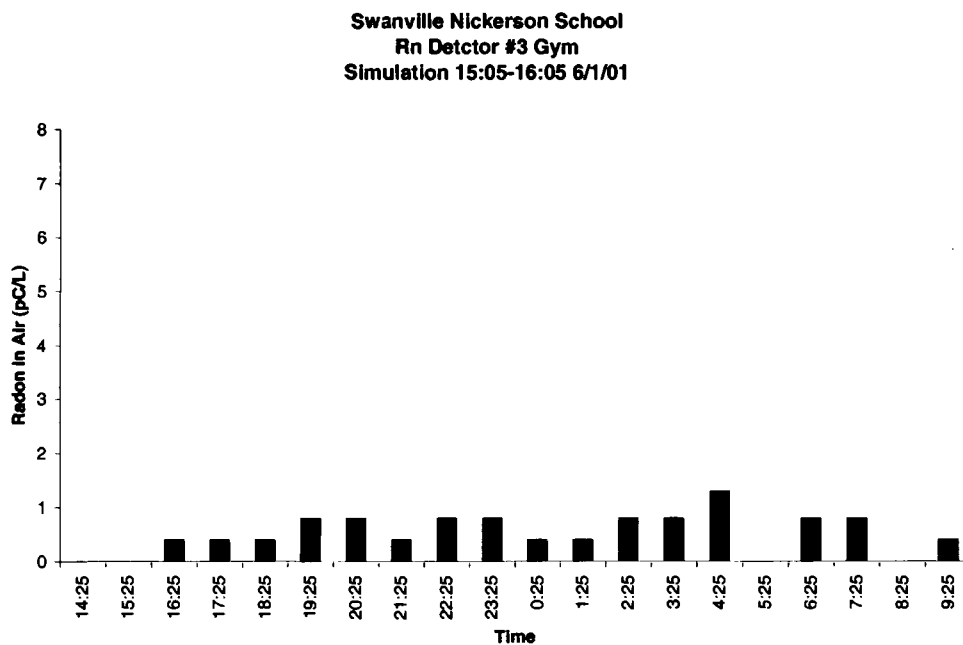


Figure A.32: Swanville Radon in Air, 9

Swanville Nickerson School  
Rn Detector #4 Kindergarten Room  
Simulation 15:05-16:04pm 6/1/01

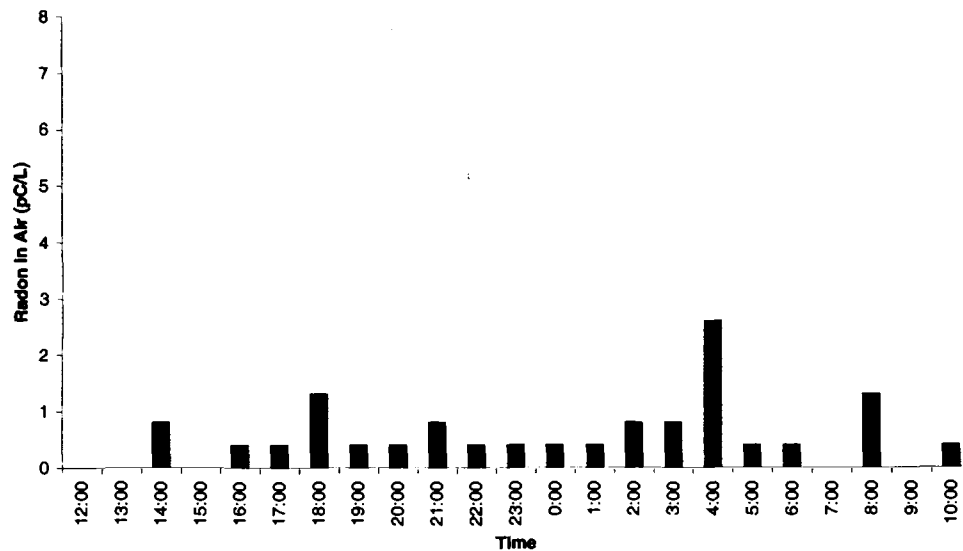


Figure A.33: Swanville Radon in Air, 10

Swanville Nickerson School  
Rn Detector #2 1st/2nd Grade Classroom  
Simulation 15:05-16:05pm 6/1/01

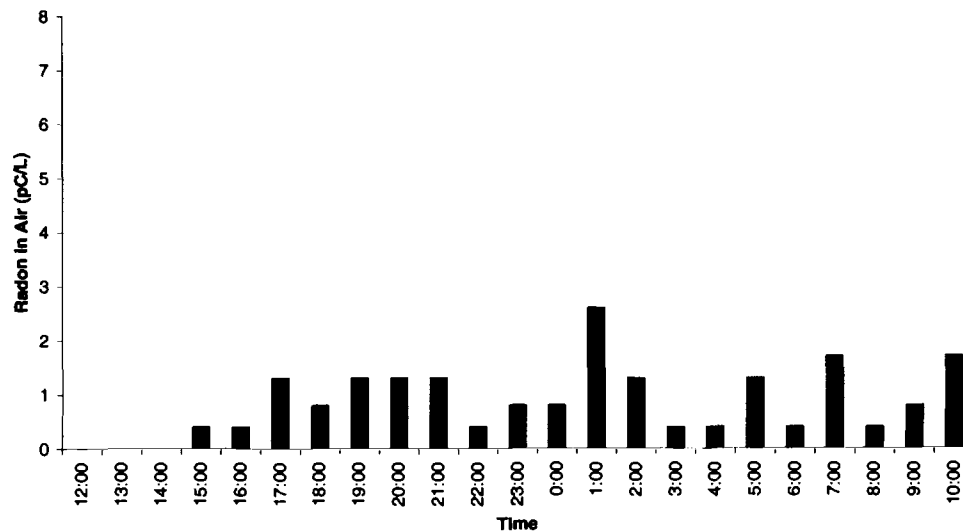


Figure A.34: Swanville Radon in Air, 11

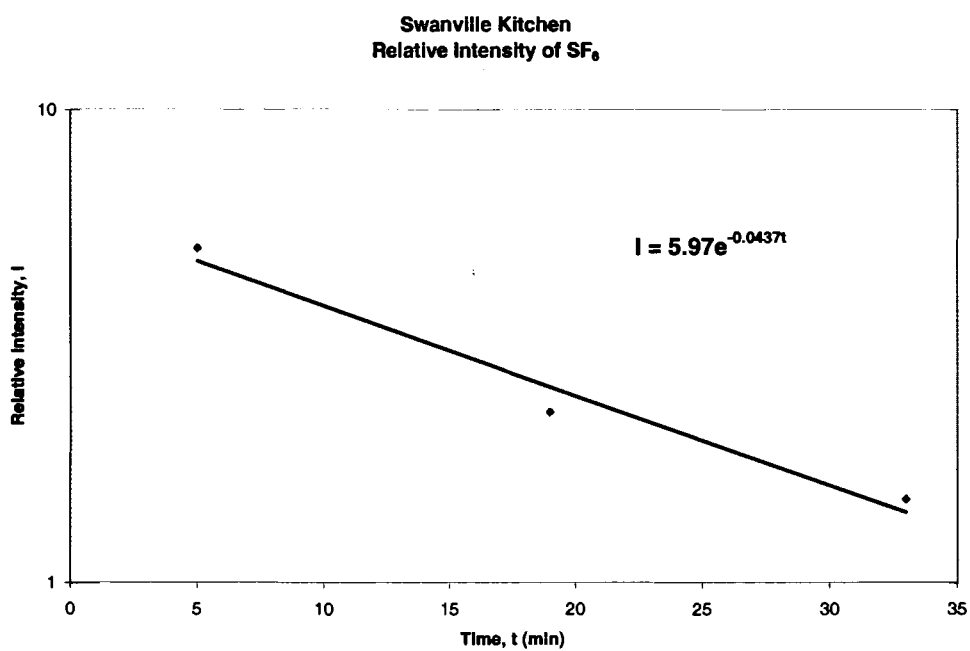


Figure A.35: Swanville Ventilation, 1

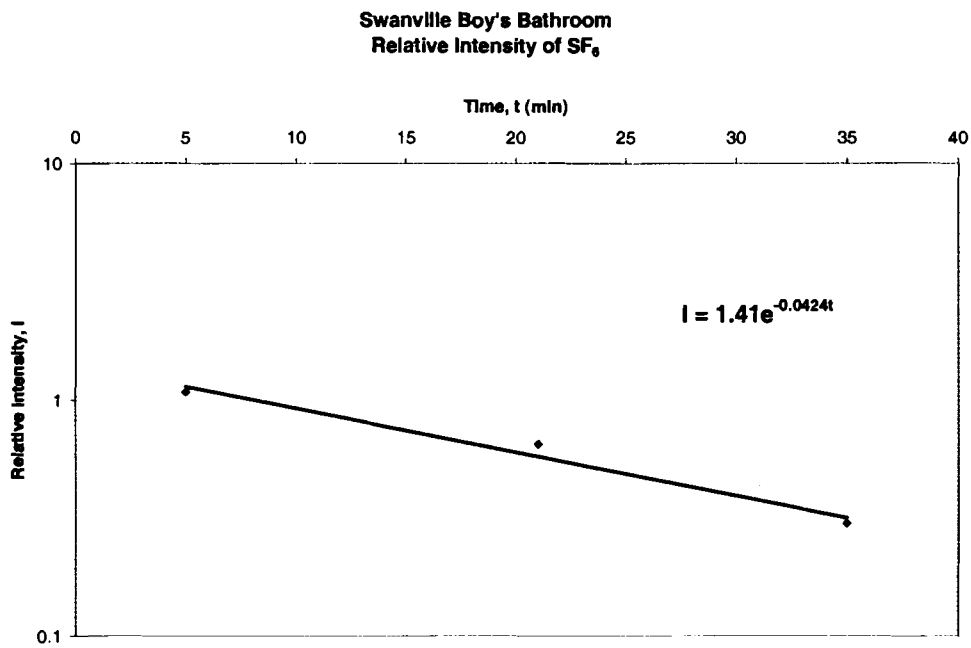


Figure A.36: Swanville Ventilation, 2

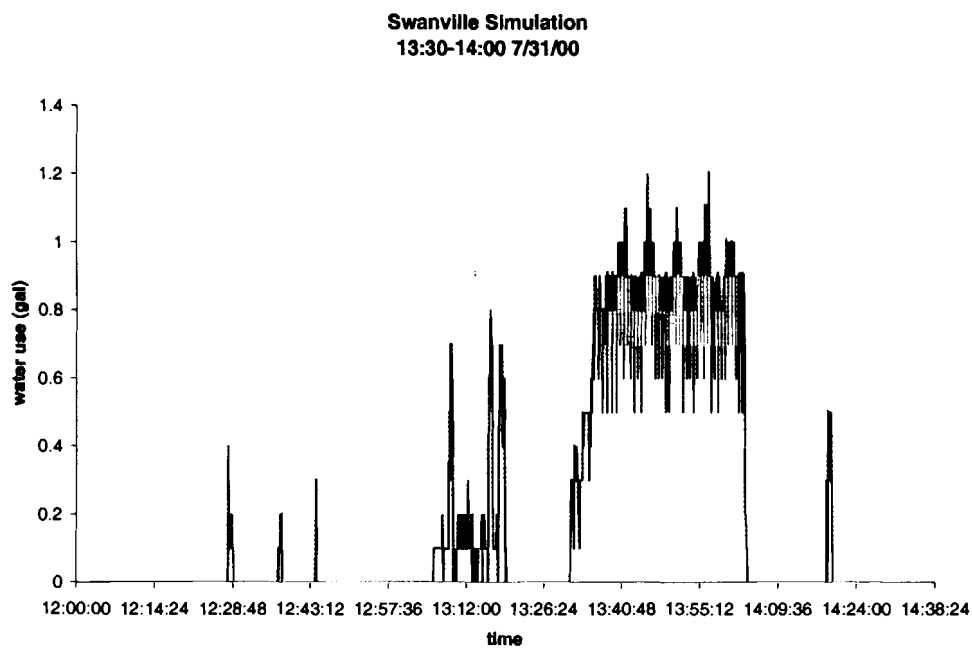


Figure A.37: Swanville Water Use, 1

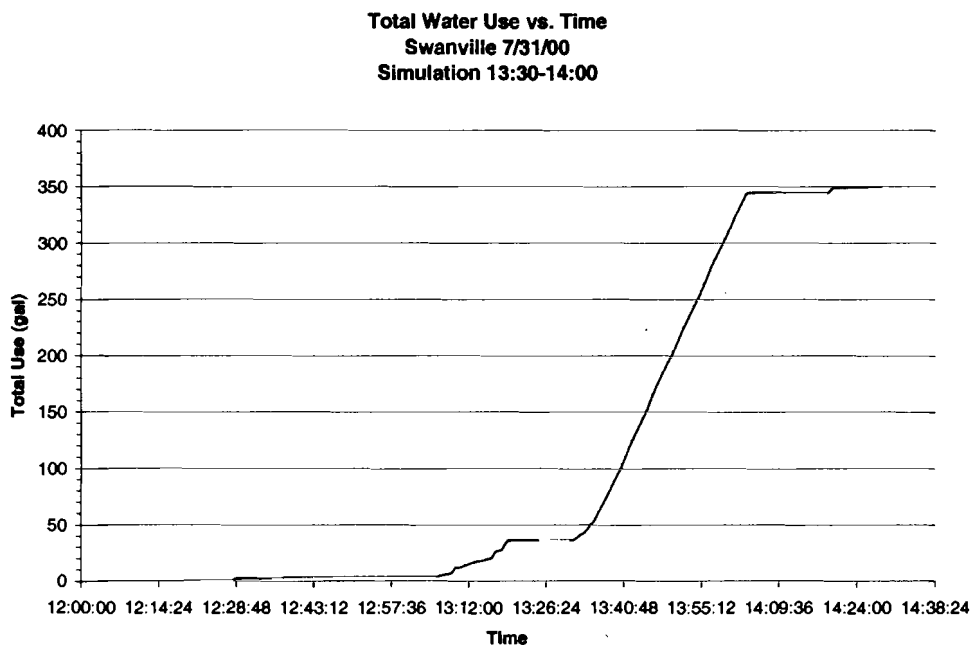


Figure A.38: Swanville Water Use, 2



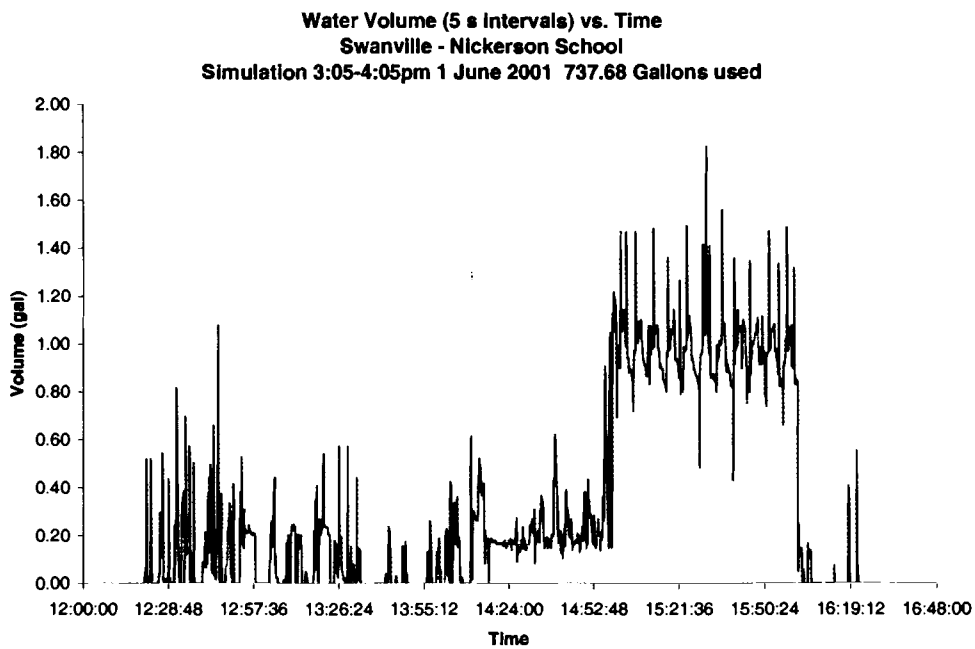


Figure A.39: Swanville Water Use, 3

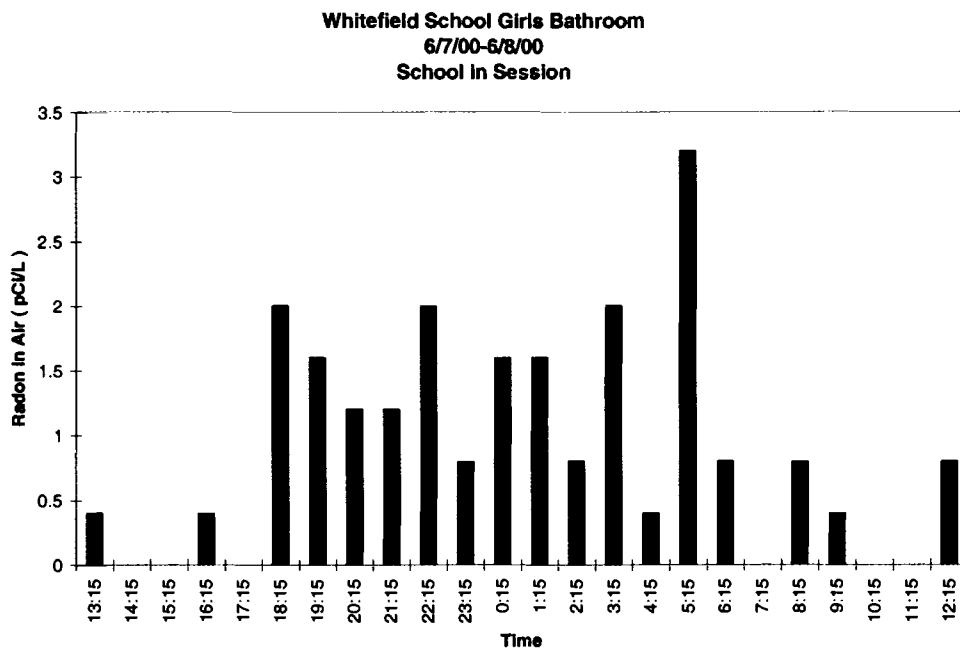


Figure A.40: Whitefield Radon in Air, 1

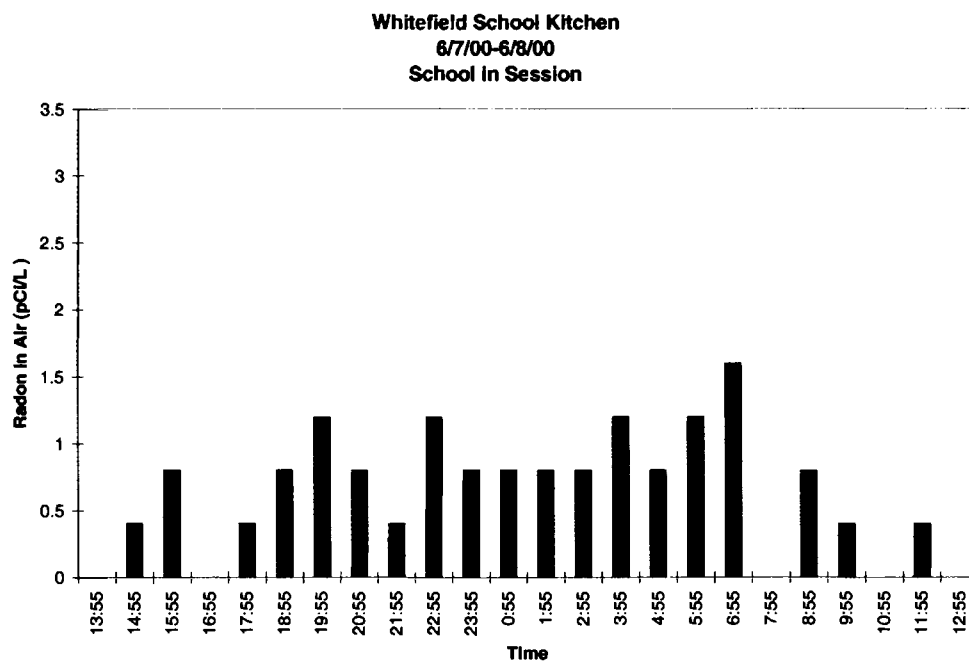


Figure A.41: Whitefield Radon in Air, 2

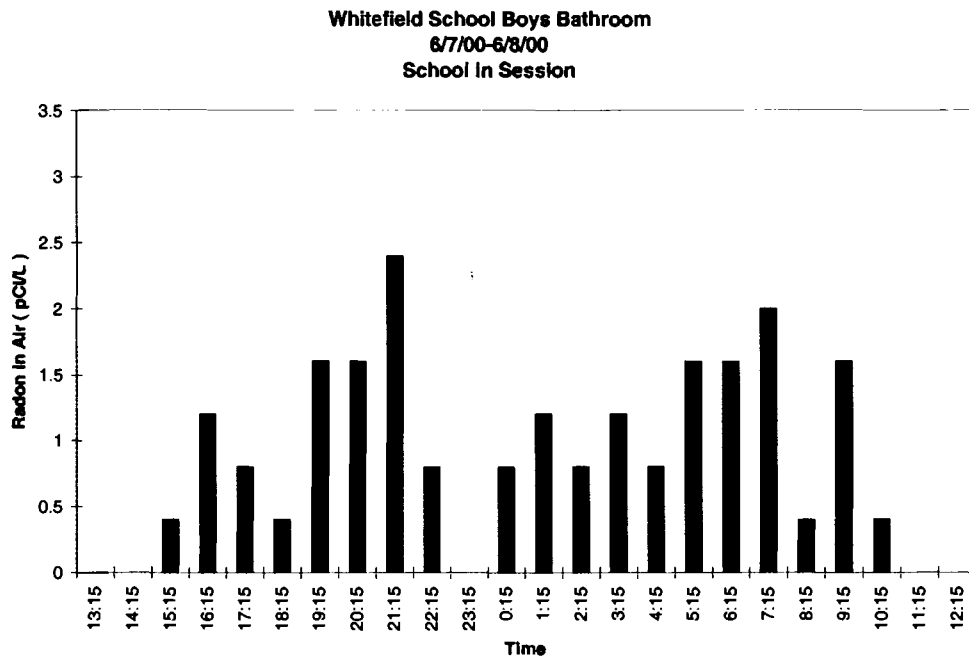


Figure A.42: Whitefield Radon in Air, 3

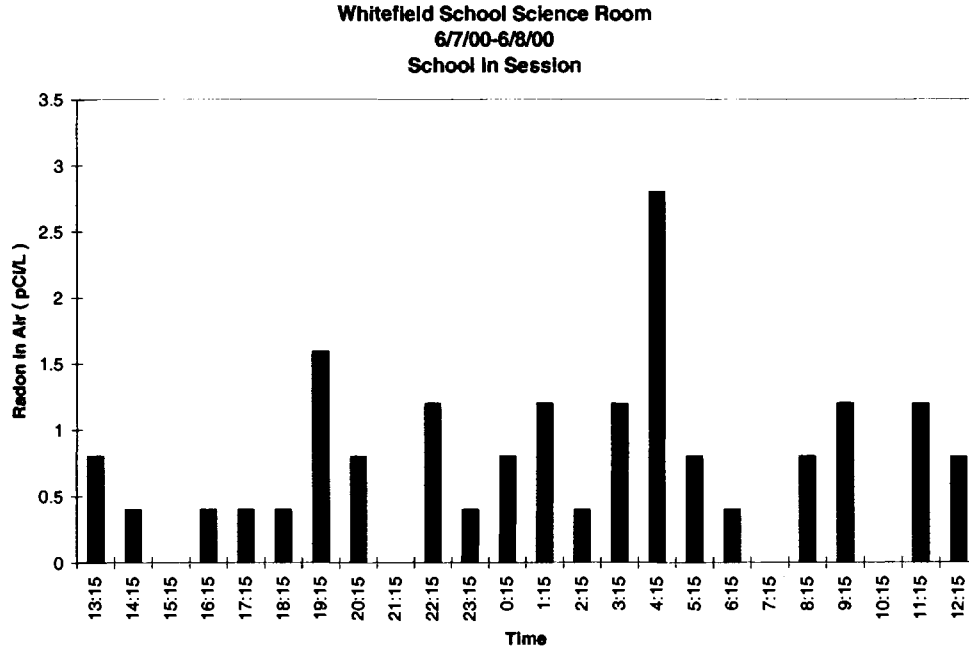


Figure A.43: Whitefield Radon in Air, 4

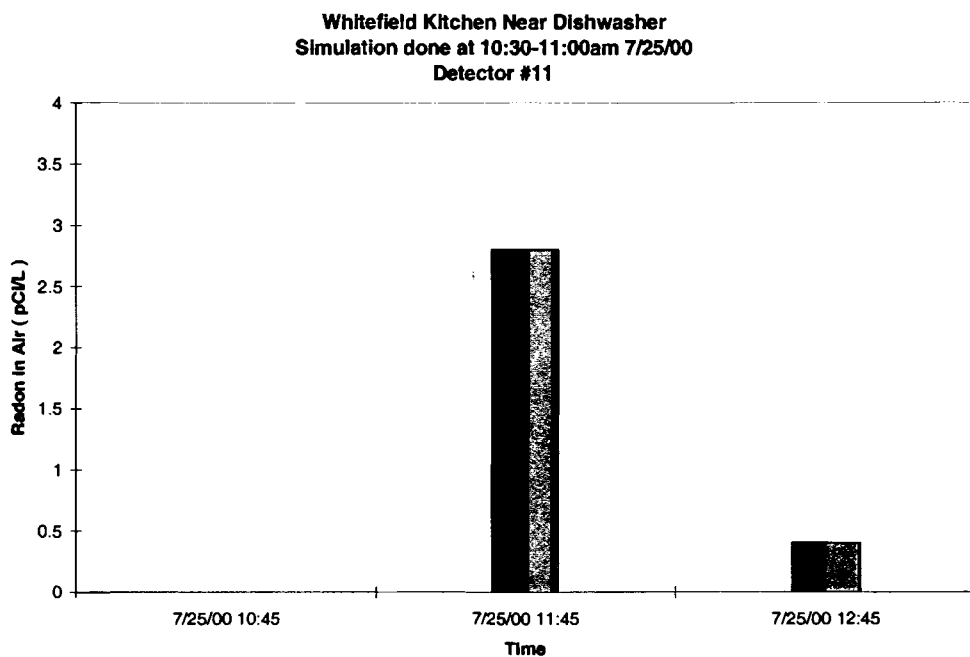


Figure A.44: Whitefield Radon in Air, 5

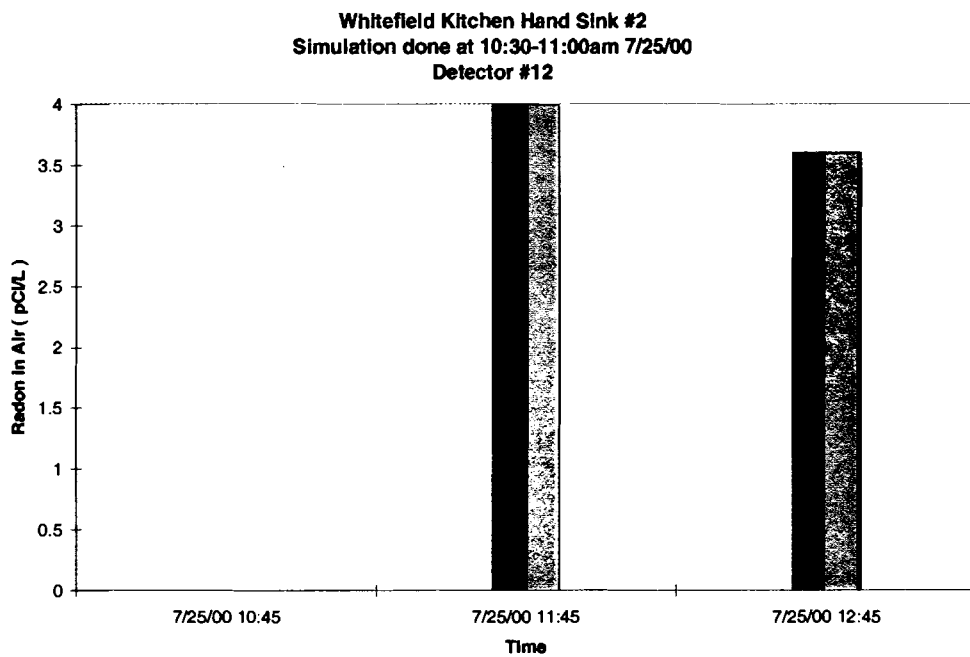


Figure A.45: Whitefield Radon in Air, 6

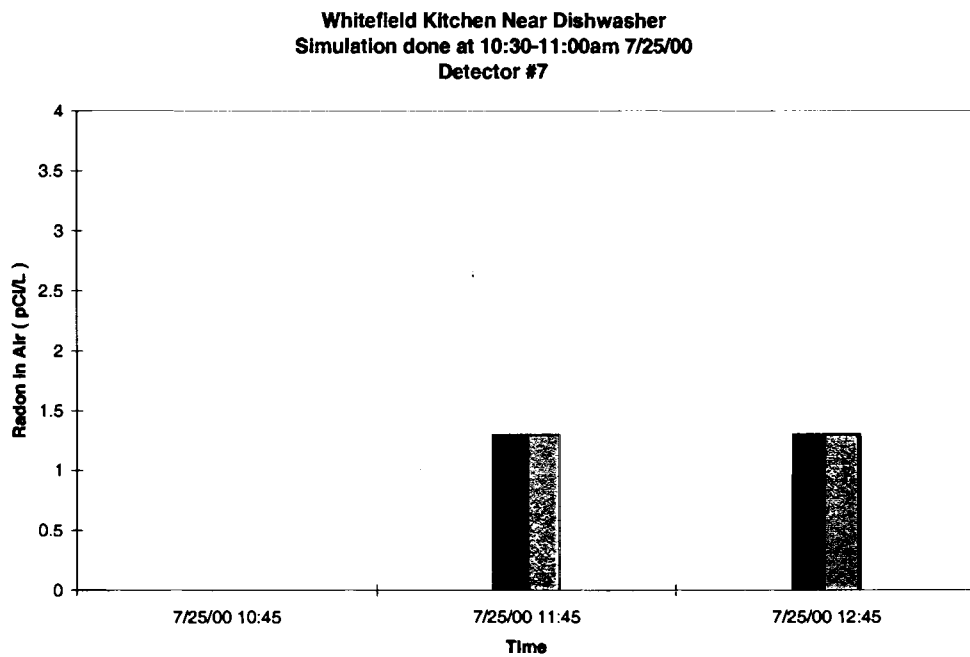


Figure A.46: Whitefield Radon in Air, 7

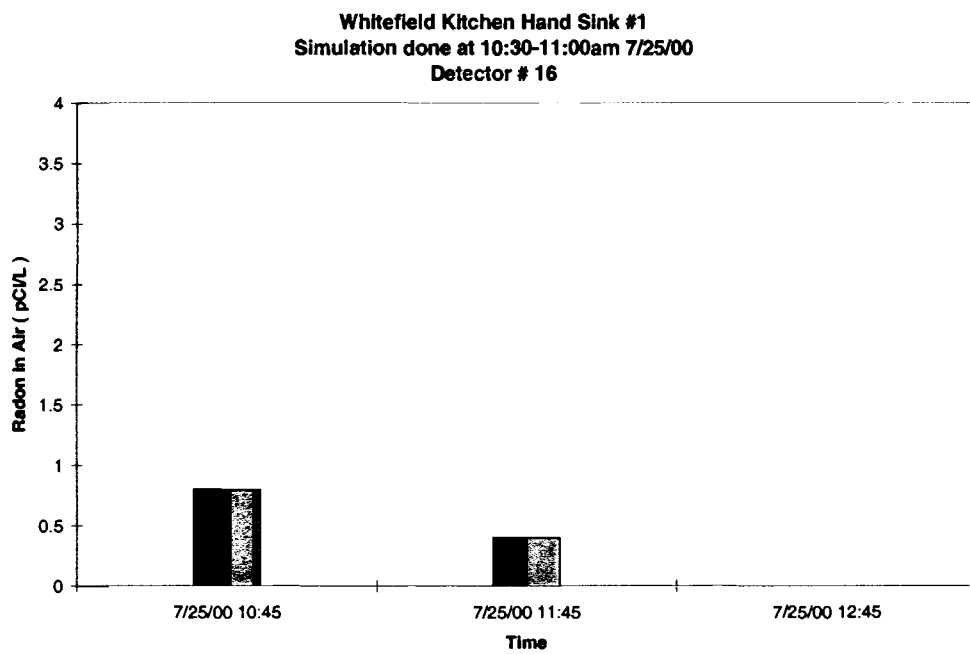


Figure A.47: Whitefield Radon in Air, 8

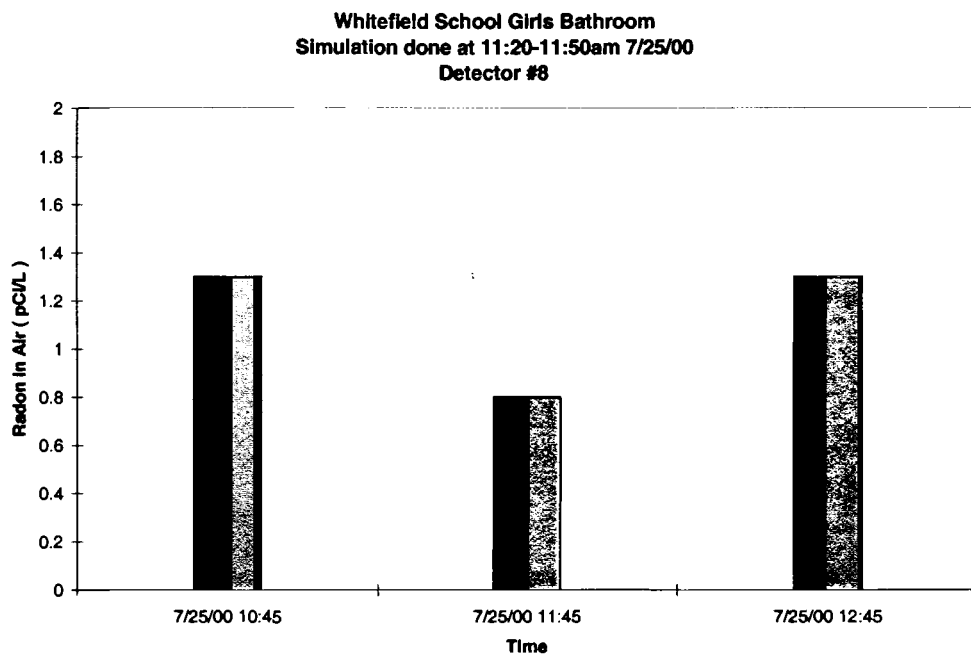


Figure A.48: Whitefield Radon in Air, 9

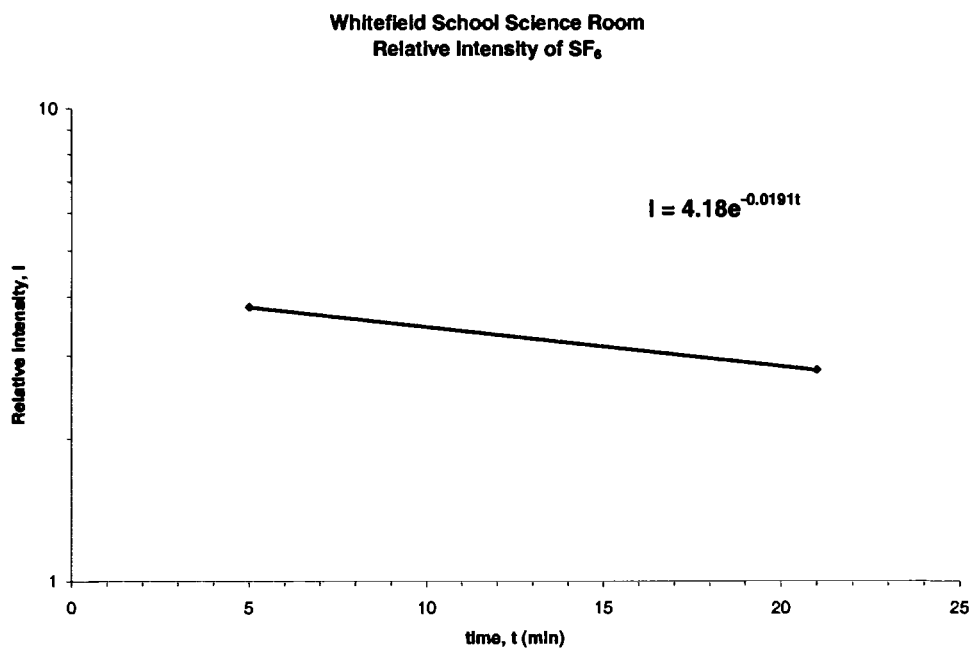


Figure A.49: Whitefield Ventilation, 1

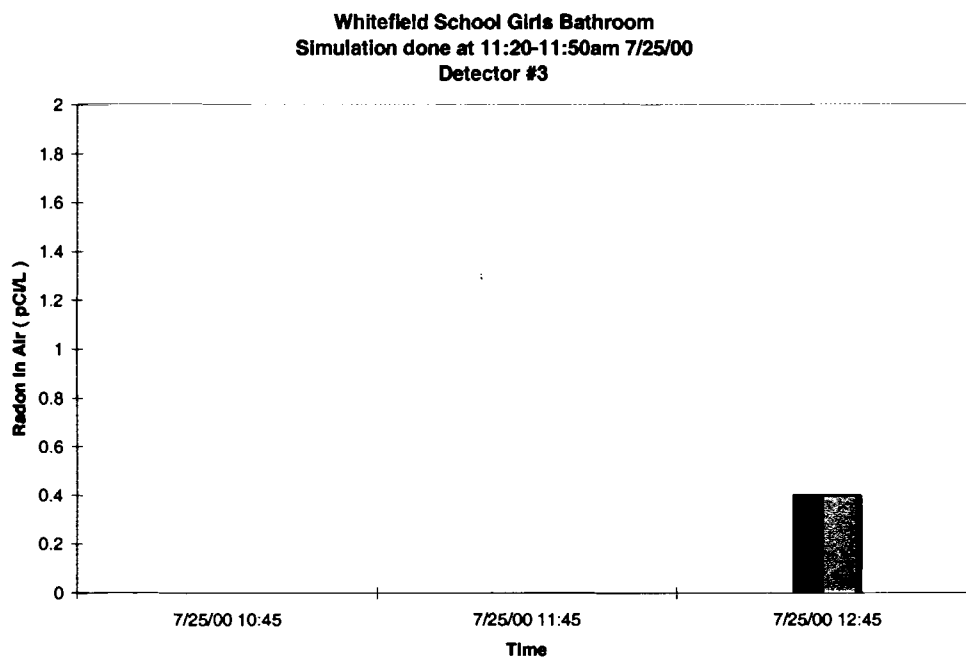


Figure A.50: Whitefield Radon in Air, 10

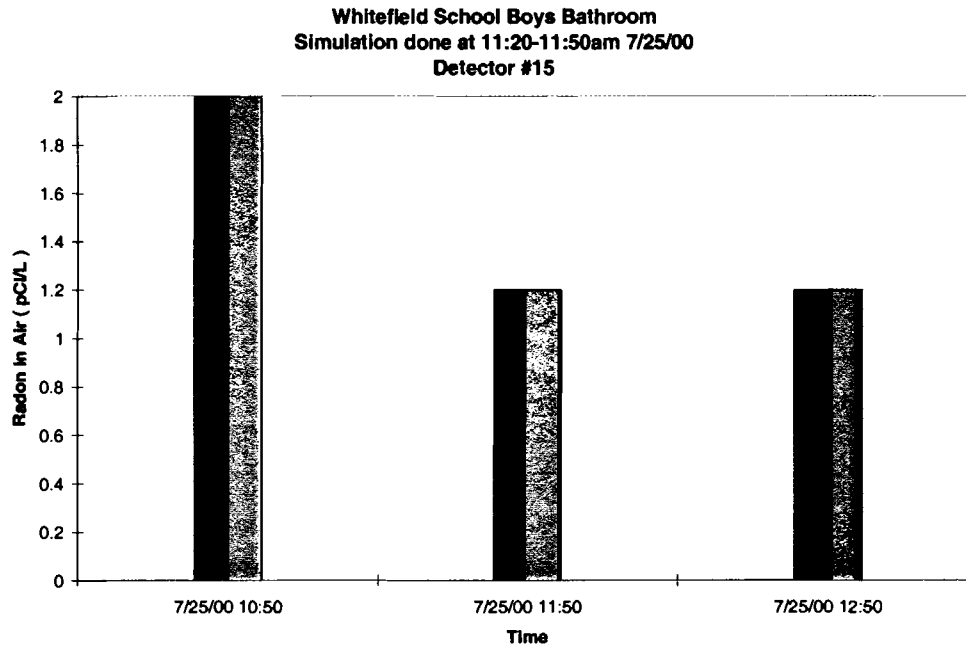


Figure A.51: Whitefield Radon in Air, 11

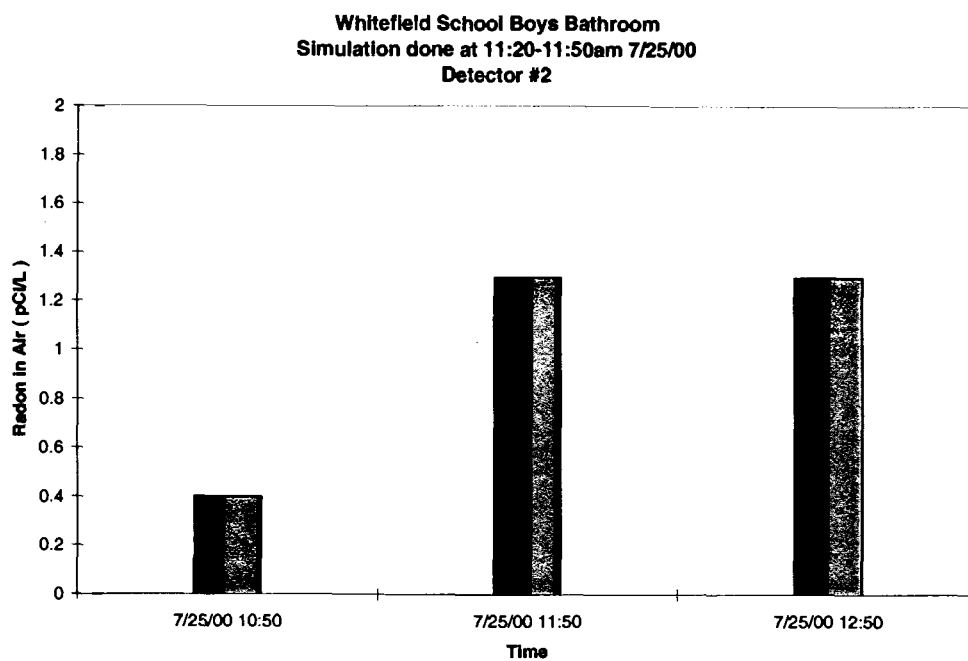


Figure A.52: Whitefield Radon in Air, 12



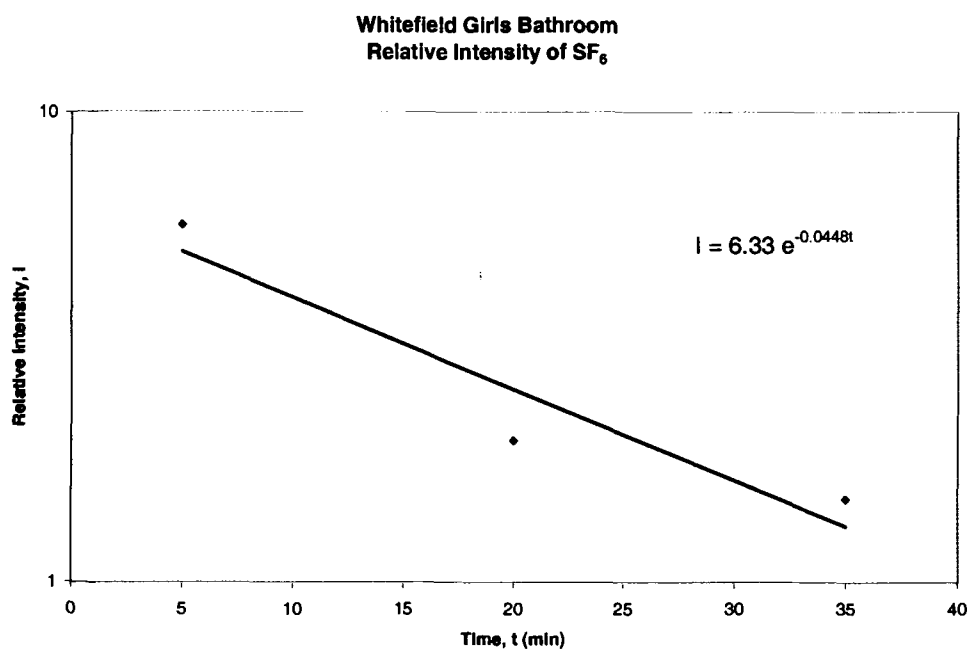


Figure A.53: Whitefield Ventilation, 2

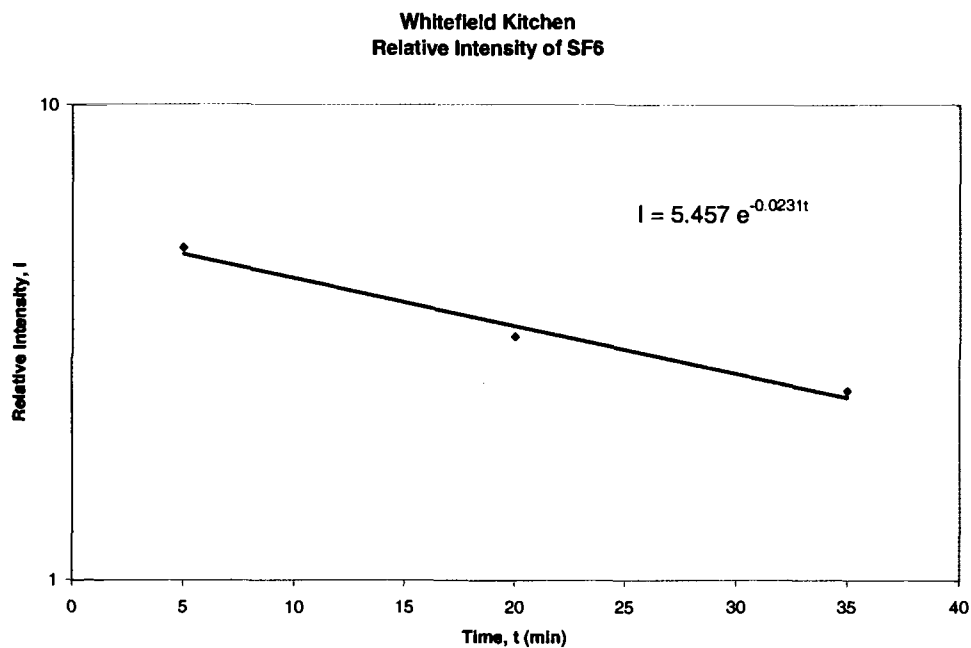
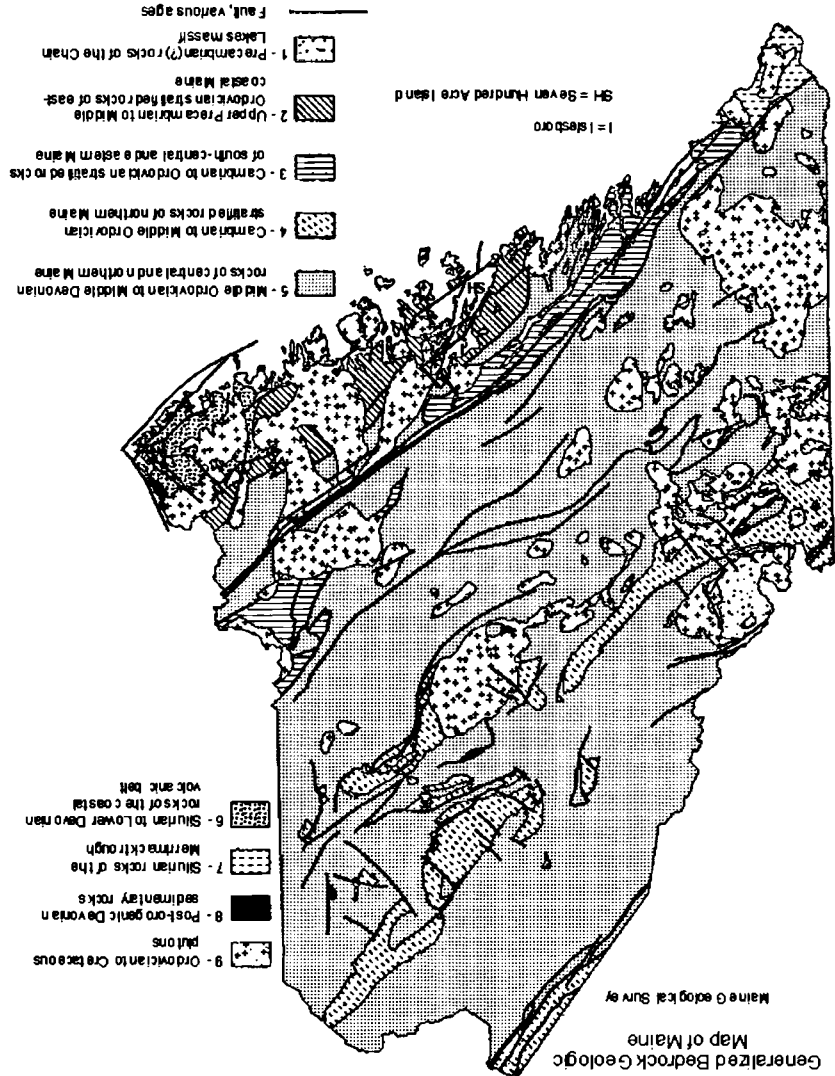


Figure A.54: Whitefield Ventilation, 3

# APPENDIX B: MAPS OF MAINE

Figure B.1: Bedrock Map of Maine



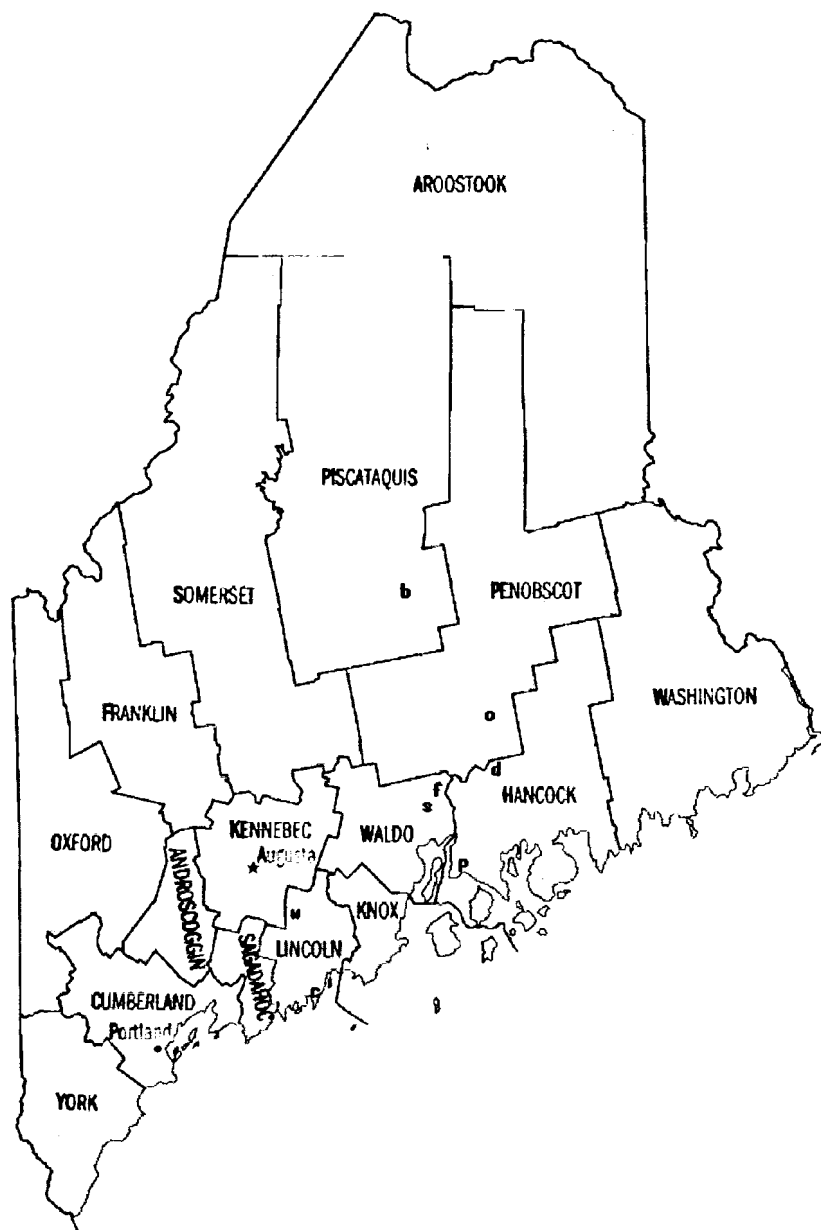


Figure B.2: Map of 8 Schools in Maine

Key for Figure B.2:

o = University of Maine, Orono, Maine

d = Dedham Elementary School, Dedham Maine

w = Whitefield Elementary School, Whitefield, Maine

b = Brownville Elementary School, Brownville, Maine

s = Swanville Elementary School, Swanville, Maine

c = Darling Marine Center, Walpole, Maine

f = Frankfort Elementary School, Frankfort, Maine

p = Penobscot Consolidated School, Penobscot, Maine

## BIOGRAPHY OF THE AUTHOR

Mary Jo Norris was born in Cleveland, Ohio on 29 November 1969. She grew up in Brecksville, a small town just south of Cleveland. After graduating from Brecksville High School in 1988, Mary Jo attended Ohio State University for two years. She then took five years off to work before returning to finish her undergraduate degree at Cleveland State University. She graduated with a Bachelor of Science degree in physics and mathematics from Cleveland State in 1998.

During her studies at Cleveland State, Mary Jo had the opportunity to work on a collaborative grant at NASA Lewis Research Center (now Glenn Research Center). While working in the Electro-Physics Branch at Lewis, she worked on a variety of projects including using Monte Carlo techniques for modeling atomic oxygen erosion and using atomic oxygen in art restoration.

In 1998, Mary Jo moved to Bangor, Maine to start graduate studies in the Department of Physics and Astronomy at The University of Maine in Orono. In addition to the radon study, she also worked on  $^{210}\text{Pb}$  dating of Maine lake sediments for a geology department study of mercury in the environment. In the winter of 2002, she had the opportunity to take a semester off to complete an internship at the National Academy of Sciences in Washington, DC. Mary Jo spent the internship working on the report entitled *Implications of Emerging Micro and Nano Technologies*.

Mary Jo is a candidate for the Master of Science degree in Physics from The University of Maine in August, 2002.