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ASSESSMENT OF OCCUPATIONAL EXPOSURE TO AIRBORNE ^{222}RN IN THREE MINNESOTA WATER TREATMENT PLANTS

Kerber, Joshua J; Jones, David W.; and Peterson, Karla

Joshua J. Kerber, David B. W. Jones and Karla Peterson
Minnesota Department of Health, Division of Environmental Health
St. Paul, MN, USA

ABSTRACT

Occupational exposure to radon-222 (^{222}Rn) can be a significant source of ionizing radiation. Water treatment plant (WTP) operators may be at increased risk of ^{222}Rn exposure resulting from water treatment processes. To evaluate this risk, we placed alpha track radon detectors (ATDs) and continuous radon monitors in three Minnesota water treatment plants. Results from a twenty-eight day screening study revealed integrated ^{222}Rn concentrations above EPA's action level of 4.0 pCi/L and some over OSHA's standard of 30 pCi/L for a 40-hour workweek. Elevated hourly ^{222}Rn concentrations were correlated to filter media backwash cycles when water was aerated inside the plant. Working level months were calculated for times operators were present and these results were compared to the integrated samples from the ATDs. Since occupational exposure to ^{222}Rn can exceed federal standards, it is practical to monitor WTPs where treatment processes can increase ^{222}Rn exposure to WTP operators and provide recommendations to lower operator's exposures.

INTRODUCTION

Radon-222 (radon) is a naturally occurring gas created from the breakdown of radium-226 (radium). It is released from soil gases and water, and has no color, odor or taste. Radon can travel easily through cracks in concrete or poorly sealed doors, and disperses quickly into the atmosphere. The long-term health risk of breathing radon is lung cancer. When breathing radon, the radioactive particles get trapped in the lungs, and as those particles break down, they release small bursts of energy. This can damage lung tissue and increase chances of developing lung cancer.

The U. S. Environmental Protection Agency (USEPA) has classified radon as a known human carcinogen with breathing radon as the second leading cause of lung cancer nationwide (after smoking). The USEPA also reports one in fifteen U.S. homes has elevated levels of radon and recommends any home at or above their 4.0 pCi/L annual average guideline should be fixed to lower the radon level (USEPA 2002). Radon is one of the most extensively investigated human carcinogens and contributes to an estimated 21,800 lung cancer deaths in the United States annually (BIER VI 1999). In the investigation of worker exposure to radon, the BIER VI report reexamined the lung cancer risk associated to radon concentrations in the domestic setting.

The Miners Safety and Health Act (MSHA) regulates miner's exposure to radon while the Occupational Health and Safety Administration (OSHA) regulates occupational exposures outside of mines. One particular place where indoor radon concentrations can exceed federal guidelines is in water treatment plants (WTPs) where treatment processes may contribute to ambient airborne concentrations. Radon can be found in WTPs as a result of the breakdown of radium. Radium is often removed along with manganese in the filtration of iron and manganese from groundwater. When this radium-enriched water is aerated or backwashed, elevated concentrations of airborne radon are created. Most of the exposure to airborne radon in these WTPs can be attributed to radium accumulation in filter media, backwash waste, or sludge. Because of this potential increased risk from occupational exposure to radon, future investigations need to be conducted to determine worker exposures.

In 1999, the Minnesota Department of Health (MDH) placed alpha track detectors (ATDs) in four WTPs to measure the airborne radon levels in order to explore the potential for occupational safety issues. The test periods ranged in duration from 86 to 110 days. Duplicate or triplicate co-located detectors were placed inside each of the WTPs in areas where operators routinely spent time as part of their jobs. Detectors were placed and retrieved by MDH staff, according to applicable USEPA measurement protocols. (USEPA 1992, 1993) Results from the ATDs were integrated over the entire test period with mean concentrations for the WTPs ranging from 4.1 to 44.3 pCi/L.

An inherent limitation of the ATDs is that variability between high and low radon concentrations during the test period cannot be determined. Such variability has been reported in other WTPs where higher concentrations of radon in air were associated with specific WTP operations (Fisher et al, 1996). If higher radon concentrations occur predominantly when operators are present in the WTP, the results of an integrated sample may underestimate the operator's exposure. Conversely, if lower concentrations occur when operators are present in the WTP, the integrated results may overestimate the amount of occupational exposure received in the plant. The number of hours a specific operator was actually present inside the WTP and the radon levels corresponding to these times will affect the amount of exposure and hence, their risk. These pilot study results indicated further investigation of human occupancy is needed to better evaluate occupational exposure in these WTPs.

METHODOLOGY

The MDH performed radon measurements in each of the four WTPs that were screened in 1999. Side-by-side continuous radon measurements were taken in each WTP for twenty-eight days. In addition, two pair of co-located ATDs were placed for the same twenty-eight days inside the WTP. Times and duration of WTP operations and operator presence inside the WTP were also recorded for the test period. This more detailed breakdown of temporal patterns in radon concentrations accompanied by information regarding operations and staff presence enabled a better examination of exposure and safety concerns specific to each facility.

At each WTP, a total of four (two pairs) ATDs were deployed along with the continuous radon measurement devices for four weeks. One pair of ATDs was placed in each of the WTPs in the same position as when the 1999 measurements were taken. These ATDs were co-located as before in the previous study and a second pair was placed in a position to reflect operator exposure when not in the immediate water treatment area, such as an office or other work place. The continuous radon monitors (CRMs) were placed inside the WTPs as close to the operator's work space without interfering with operations or operator activities. Data printouts were retrieved from the CRM at the WTP once a week. To simulate a worst-case exposure scenario, the WTPs were requested to operate their WTPs as they would during cold winter months. The operators were requested to keep all doors and windows closed for the duration of the entire test and to limit the amount of entry and exit into and out of the building.

Operators at each WTP recorded information regarding operations occurring in the WTP (backwashing, pumping rates, and any abnormal conditions) and each operator completed a log sheet for the time they spent inside the WTP.

All monitoring results obtained with the CRM were entered into a database allowing the correlation of radon concentrations with times operators are present inside the WTP and preceding activities at the WTP that may influence the airborne concentration of radon gas. Continuous sampling results from the CRM were used to describe temporal variability of airborne radon concentrations and any relationships to water treatment activities. Time-specific hourly radon average concentration and operator presence information was used to estimate time-weighted-average exposures to individual operators and perhaps improving on the exposure estimates that could be derived using only a long-term integrated sample result. Exposures estimated through time-weighting are compared to those derived using the long-term ATD measurements to evaluate the utility or limitation of using only a long-term integrated sample result to measure operators' exposures. Time-weighted-average exposures were calculated as shown in figure #1. However, since the equilibrium ratio (ER) may not be the same for each instance when the same concentration of radon is measured and because ER was not measured specifically, an assumed average ER value of 1.0 was be used as a default (Fisher, et al, 1996). This assumption can be used to simplify the above equation and is shown in figure #2.Operator presence inside the WTP was estimated from the operator log sheets which indicated presence inside the WTP for any of the fifteen-minute quarters of an hour corresponding to each hourly-integrated radon measurement. Thus, the time parameter for exposure calculations was determined in 0.25, 0.5, 0.75 or 1.0-hour increments. These estimated cumulative radon exposures were then interpolated from twenty-eight day WLM exposures to 365 day, or annual WLM exposures.

Occupational exposure limits for radon vary by regulating agency. The Environmental Protection Agency recommends the average indoor radon concentrations in homes be kept below 4.0 pCi/L in order to minimize exposure and reduce lung cancer risk. OSHA regulates exposure to radon gas and its decay products for workers other than underground miners and their exposure standards are used for comparison in the WTP scenarios. According to OSHA, radon exposures should be limited to either 30 pCi/L or 0.33 WL based upon a continuous workplace exposure for 40 hours per week, 52 weeks per year. Simply, the occupational exposure received by a operator in a WTP should be limited to no more than four WLM per year (USDOL 1999).

Other guidance values for radon in indoor air or in occupational settings also exist. For example, the National Council on Radiation Protection and Measurements (NCRP 1984) recommended remedial action be taken to limit an individual's total exposure to two WLM per year in buildings. Exposure estimates from both the ATDs and CRMs will be compared to each other and to the guidelines recommended by the agencies discussed above.

RESULTS/DISCUSSION

In early 2003, the Minnesota Department of Health conducted a follow-up study of indoor radon in three WTPs. Similar studies have been conducted in the neighboring states of Iowa and Wisconsin with similar results (Fisher et al, 1996, Nelson 2002). Following are the results from a twenty-eight day follow-up study from one Minnesota WTP.

The WTP was constructed in 1998 and treats water from one well located in east central Minnesota. The water source for the WTP comes from a 397'-deep well and produces 350 gallons of treated water per minute. The average raw and finished radon in water concentrations during the study are 1236 pCi/L and 1988 pCi/L with a standard deviations of 264.63 pCi/L and 1064.58 respectively. In addition, the most recent average raw and finished radium in water concentrations were 7.6 pCi/L and 3.3 pCi/L respectively. The WTP has a single Lshaped room with a large pressure filter in the center. The tank is constructed out of steel, is ten feet in diameter and twenty-two feet long, with greensand filter media, and was designed to filter iron and manganese. This WTP also removes radium during filtration which may contribute to radon in air concentrations within the WTP. There is a large drain opening for the backwash water to drain into located near the north corner of the building. A corner-mounted space heater is the only source of heat for the single-roomed WTP and ventilation is very limited.

During the four-week testing period, the WTP operator typically arrived each day around 8 AM and stayed for fifteen minutes. Twice a week an operator would come back in the afternoon for fifteen to sixty minutes to perform the backwash cycles. Backwash cycles are initialized manually for each of the four cells in the tank and lasted fifteen to twenty minutes each for a total of sixty to eighty minutes. This process was completed six separate times over the study period; twice a week during weeks one and two, then only once a week during weeks three and four. During these backwash cycles, not only was at least one operator present, but also the hourly radon concentrations peaked at over 200 pCi/L.

Two ATDs and two CRMs were placed on the work desk twenty-six feet away from the backwash drain while another set of ATDs was placed on an electrical panel six feet away from the backwash. Results from these ATDs averaged 33.9 and 35.8 pCi/L with coefficients of variation of 10.6 % and 0%, for the backwash and work desk areas, respectively. Hourly radon concentrations ranged from a minimum of 0.4 to a maximum of 217.4 pCi/L and are shown with operator presence and backwash times in figure 3.

Typical hourly radon concentrations between backwash cycles fluctuated between 2.0 and 12.0 pCi/L, but when the backwash cycles were initiated, hourly radon levels rose drastically by a magnitude of ten to twenty times the normal average. Furthermore, when the radon levels were at their highest, the WTP operators were also present in the building. Once the backwash cycles had begun, it took an average of 41 hours for the hourly radon concentrations to return back to normal WTP levels. These weekly hourly concentrations are illustrated in figures 4-7.

Using the hourly radon concentrations coupled with the operator logs, each operator's accumulated exposure can be calculated. Exposure estimates for all six of the individuals who worked in the WTP over the twenty-eight day screening test are shown in Table 1. Exposure times ranged from just 0.25 hour up to 10.25 hours. The operator with the most logged hours is also exposed to the highest hourly radon concentrations. Although the operator was in the WTP for 10.25 hours during the study, his estimated annual exposure approached one WLM. Another operator who was only in the WTP for 1.5 hours has approximately the same annual exposure estimate as the operator who spent 9 hours in the WTP.

From the results of this study, MDH makes the following recommendations to lower occupational exposure to airborne radon. The most important factor in lowering radon concentrations is ventilation. Natural or mechanical ventilation should be moved, added or increased to lower the radon levels. This can be accomplished by adding or modifying existing mechanical ventilation systems to the backwash areas. If the weather permits, it may be accomplished by opening doors and windows. Removing radon concentrations from the backwash and/or aeration areas by exhausting the ambient air outdoors is potentially another way to lower radon concentrations within the WTP. Other steps that may be taken include replacing or cleaning the filter media more often and taking other appropriate steps to lower the radium levels on the filter media. By separating the backwash sump from the rest of the WTP or automating the backwash cycles when operators are not present, the WTP operators will lower their exposures. Limiting exposure in the WTP when elevated levels of indoor radon are known will also lower occupational exposure to radon. Designing future WTPs with a separate well-ventilated area for performing backwash cycles is another good way to lower occupational radon exposures.

When testing WTPs for occupational radon exposure, it is prudent to place CRMs for a minimum of two weeks or two separate backwash cycles, which ever is greater. Using CRMs allows operators to get a better estimate of their occupational exposure during the periods when the radon concentrations are at their highest. It will also allow operators to evaluate data whether or not staff is present. The use of CRMs is preferred over ATDs because of the inherent inability of the integrated samples to estimate short-term variability of the radon concentrations. By using CRMs and an WTP operator log sheet, operators can calculate their occupational exposures to ensure they are below federally accepted guidelines.

CONCLUSIONS

The Minnesota Department of Health completed an assessment of airborne radon in three WTPs in Minnesota on February 26, 2003. Results from the survey indicate very elevated hourly radon in air concentrations related to operations within the WTPs. All three WTPs are designed to filter iron and manganese, and each WTP backwashes their filters at least once every two weeks. Iron and manganese filtration can also remove radium, and as a result, it cab inadvertently accumulate radium on the filter media. Backwashing these filters with the radium enriched water can then drastically increase the amount of airborne radon concentrations when the water is splashed into the drain. Elevated spikes in the hourly radon concentrations coincided with the backwashing of the filters, during which the operator was usually present in the WTP.

Due to the short exposure periods for most of the operators, none of the occupational exposures to radon were above the OSHA guideline of four WLM or the NCRP guideline of two WLM. However, if operators are exposed to higher levels of radon, or are exposed for longer periods of time, then some operators may accumulate enough exposure to exceed the OSHA or NCRP guidelines. An OSHA requirement for workplaces with radon exposures above 7.5 pCi/L is to post "Airborne Radioactivity Area" signs if the area is occupied for 40 hours per week for 52 weeks a year (CFR 29, 1910:1096). This would include the east central Minnesota WTP but only if the WTP was occupied for 40 hours a week. Nevertheless, the concentration of radon measured in all three WTPs was above the 4.0 pCi/L annual average guideline suggested by USEPA for residential settings. Regardless of the calculated risks, the principle of reducing indoor radon concentrations in occupied spaces wherever reasonably achievable is the most health-protective position to take.

A comparison between cumulative exposure levels and single integrated sample exposures was also made. During this study, continuous exposure estimation from the CRMs seemed to be more accurate than using the ATDs. The majority of ATD's annual exposure estimates were far below the estimated accumulated exposures calculated from the CRMs. This is most likely due to the operator presence in the WTP when airborne radon concentrations were elevated; usually during and shortly after the backwash cycles were initiated. Limiting the operator's presence during these times will reduce their exposure and hence, risk.

Steps should be taken to reduce occupational exposure to airborne radon levels in WTPs by increasing ventilation continuously or during backwash events, locating the backwash sump in a separate well-ventilated room, minimizing radium accumulation on the filter media, or using automatic backwash controls. Removing operators until hourly radon concentrations are reduced from the backwash levels would also be acceptable, especially when many WTP operators have other responsibilities outside of the WTP.

This study has some inherent limitations. The ER was not derived so it was assumed to be 1.0 and the annual exposures in WLMs was estimated from a short amount of time. These exposure estimates may change with an increase or decrease in local water usage and natural ventilation during warmer weather. It would be more advantageous to conduct longer screening periods. In addition, the number of WTPs screened was very small and the results will be difficult to apply to the entire population of Minnesota WTPs. Each WTP would need to conduct their own radon exposure assessment. In order to get a true representation of the operator's overall radon exposure, radon tests would also need to be conducted at the homes of the operators.

It is prudent to further investigate occupational radon exposure in WTPs. Studying more WTPs and exploring how WTP characteristics and levels of radon and radium in the water affect the indoor air concentrations may yield a better understanding of how WTP processes influence occupational radon exposure. Investigating how increased ventilation rates and other mitigation strategies will affect radon concentrations may aid in the design of future WTPs and lower occupational radon exposure. Occurrence of airborne radon should be considered in the design and renovation of future and existing WTPs. Perhaps the most important factor in investigating occupational exposure to radon is educating WTP operators, designers and builders of the potential exposure to high radon concentrations during the water treatment process and practices that could reduce occupational radon exposures.

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TABLES AND FIGURES

$$WLM_{total} = (1/170)\,[(ER)_1\,([Rn\text{-}222]_1/100)\,(Hours)_1 + \ldots + (ER)_n\,([Rn\text{-}222]_n/100)\,(Hours)_n]$$

Where $(ER)_{1 \ldots n}$ = the radon: radon progeny equilibrium ratio for each Rn-222 concentration 1 to n.

$Hours_{1 \ldots n}$ = the total number of hours an individual operator is present inside the WTP for each Rn-222 concentration 1 to n.

Figure 1. Time-Weighted-Average Exposure Equation

$$WLM_{total} = (1/170)(ER)\,[([Rn\text{-}222]_1/100)\,(Hours)_1 + \ldots + ([Rn\text{-}222]_n/100)\,(Hours)_n]$$

Where (ER) = 1.0

$Hours_{1 \ldots n}$ = the total number of hours an individual operator is present inside the WTP for each Rn-222 concentration 1 to n.

Figure 2. Simplified Time-Weighted-Average Exposure Equation

Operator Initials	Hours in Plant	Monthly Work Exposure (WLM)	Annual Work Exposure (WLM)	ATD Average (pCi/L)	ATD Based Exposure (WLM)	ATD Based Annual Exposure (WLM)
CV	2.25	0.0198	0.2607	34.9	0.0046	0.0601
DB	0.25	0.0001	0.0018	34.9	0.0005	0.0067
JHL	6.00	0.0339	0.4458	34.9	0.0123	0.1603
JW	9.00	0.0117	0.1538	34.9	0.0185	0.2405
SH	10.25	0.0760	0.9983	34.9	0.0210	0.2739
TK	1.50	0.0119	0.1557	34.9	0.0031	0.0401

Table 1. Estimated Occupational Exposures Based on CRM Data

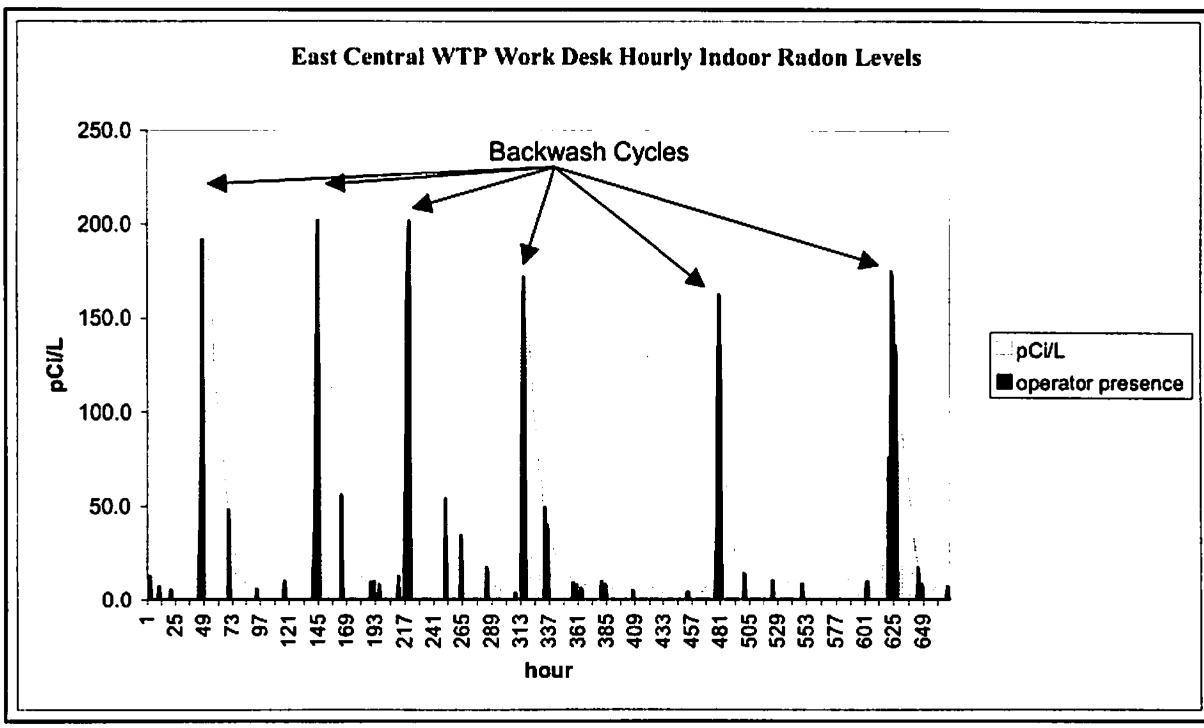

Figure 3. Hourly Radon Concentrations from January 22 – February 19, 2003

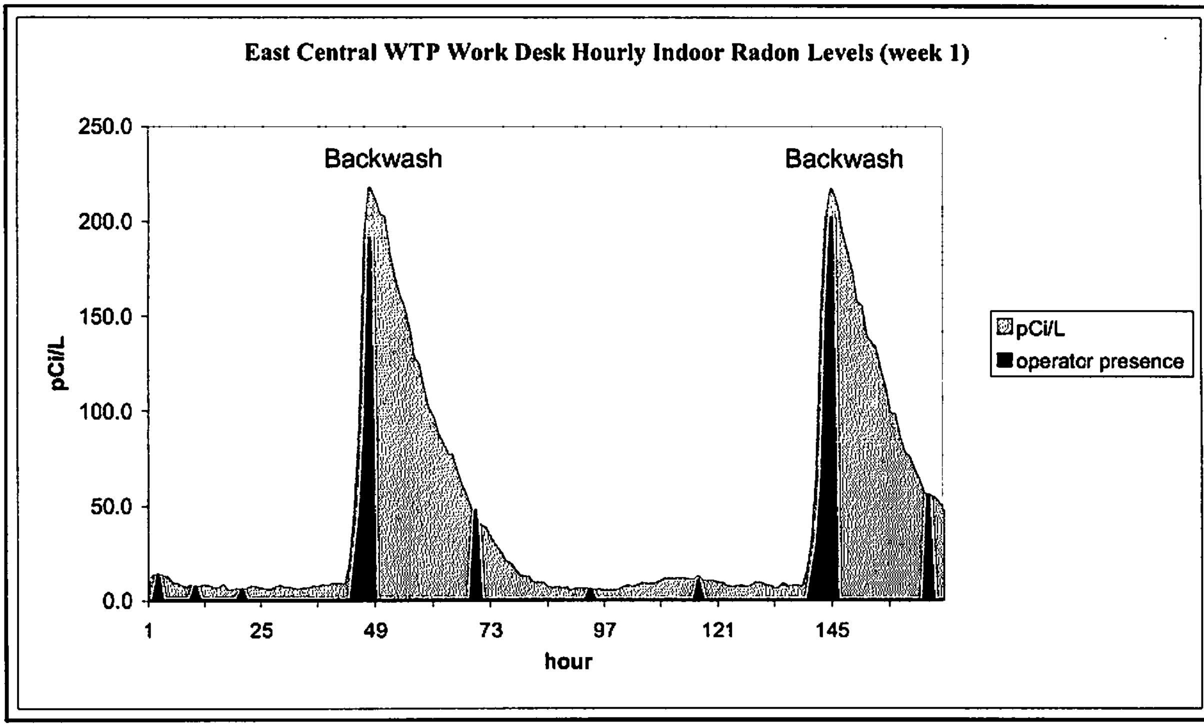

Figure 4. Hourly Radon Concentrations from January 22 – 29, 2003

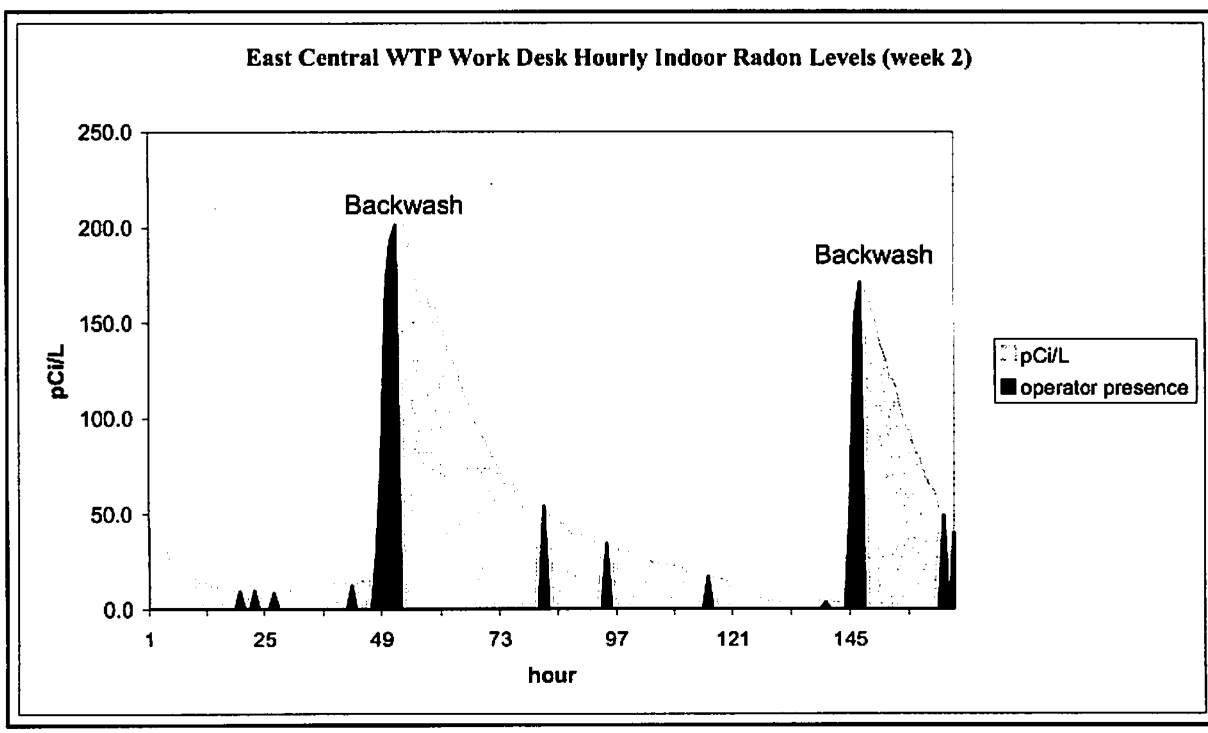

Figure 5. Hourly Radon Concentrations from January 29 – February 5, 2003

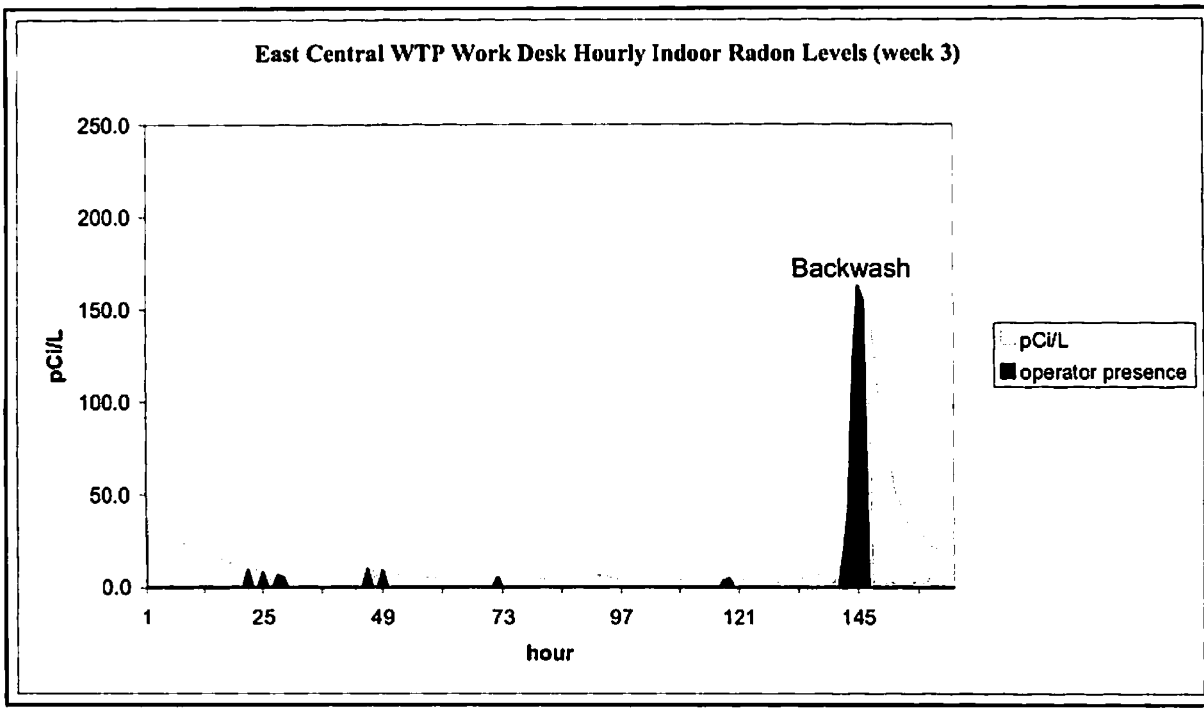

Figure 6. Hourly Radon Concentrations from February 5 – February 12, 2003

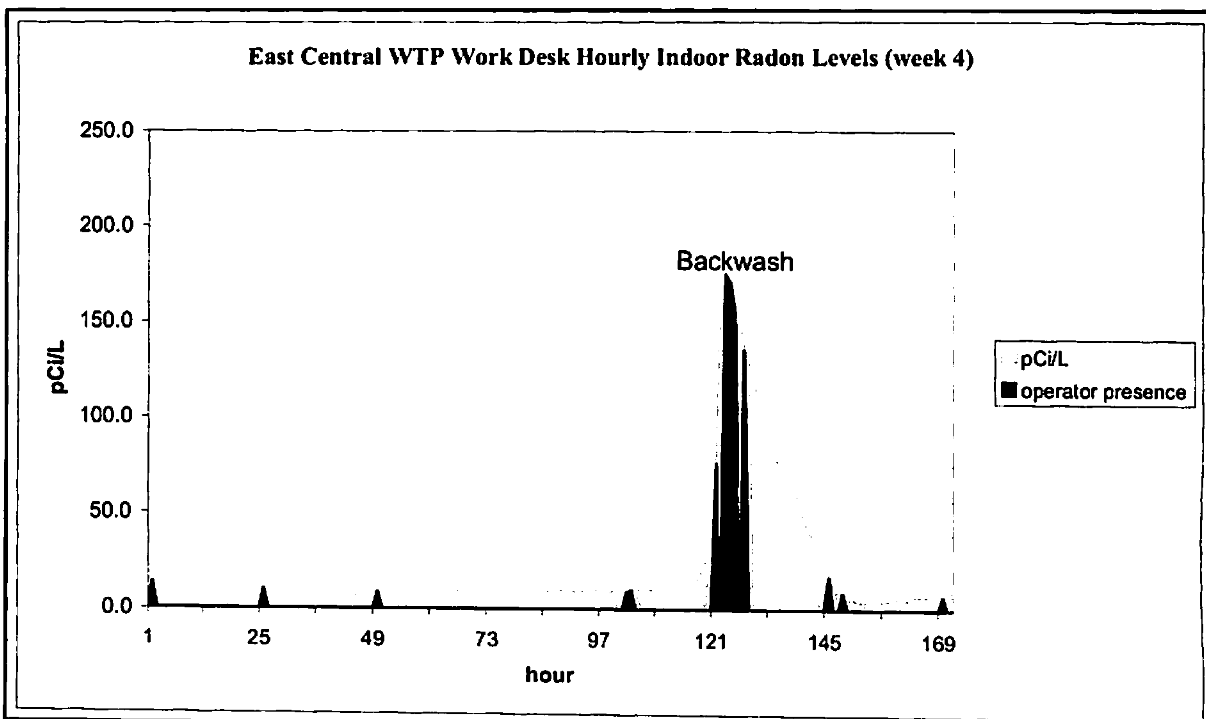

Figure 7. Hourly Radon Concentrations from February 12 – February 19, 2003