EMPLOYEE EXPOSURE TO RADON-222 AND THORON-220 IN THREE FISH CULTURE STATIONS IN PENNSYLVANIA

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Abstract

Employee exposures to Radon-222 and Thoron-220 were measured in three Commonwealth fish hatcheries using specially designed personal dosimeters to determine whether remediation might be necessary. Employees utilizing the hatch house would wear the dosimeter and keep track of their time in the hatch house. Area detectors were also deployed full time in each hatch house. Exposure measurements were compared to NRC, EPA, and OSHA exposure limits. All measured employee exposures to Radon-222 and Thoron-220 were very low and well below currently established regulatory limits. However, hatch house radon concentrations are significantly elevated above the U.S. Environmental Protection Agency residential guideline of 148 Bq m^{-3} (37 Bq m^{-3} = 1 pCi/L).

Key words: Radon-222; Thoron-220; Radon/thoron in water; employee exposure

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Introduction

The Pennsylvania Fish and Boat Commission operate 14 fish culture stations throughout the Commonwealth. The exclusive purpose of this operation is to provide stocked fish in Commonwealth lakes and streams for licensed anglers. Both warm water and cold water species are raised and stocked. The majority of the fish culture stations uses ground water, either spring or well water, for their daily operations. Additionally, the daily amount of water use can be significant, well into the hundreds of thousands of gallons per day.

The measurement of radon-222 in both water and air at these 14 facilities is described in a previous paper by this author (Lewis 2001). Three out of the 14 facilities were found to have elevated radon concentrations of concern in the hatch house, during our previous survey. It is these three facilities that are the focus of this study. For this paper those facilities are coded B, BS, and C.

Other investigators (Dwyer and Orr 1992; Kitto 1998; Harris and Craig 1991; and Stillwell 2008) have also found high radon levels in similar facilities in Montana, New York, Missouri, and Maine, respectively.

The mechanism of action is that gaseous radon-222 (radon) or radon-220 (thoron) diffuses from the rocks and soil surrounding the well or spring into the facility water supply. Flows can be very variable, but typically ranges from ten's to several thousand liters per minute. This water is drawn into the hatch house (HH) for the rearing of the young fish. Due to the high Henry's Constant for radon in water, which at 20 degrees centigrade and 1 atmosphere is 2200, there is a strong tendency for radon to off-gas into the surrounding air of the hatch house. Ground water can often be saturated with nitrogen, depending upon the area of the state, and also have very low oxygen levels. Both of these conditions are deleterious to fish production. Due to these conditions many of the hatch house facilities use various aeration techniques on the influent water supply within the enclosed structure to drive off nitrogen and increase the oxygen; this also favors the release of the waterborne radon, and presumably any thoron into the hatch house air. This mechanism provides for one pathway for both radon and thoron exposure to hatch house personnel. Another mechanism of possible exposure is from the radon/thoron in soil gas. This is the gas contained in the soil directly below the foundation of the building. This is the typical route of gas entry into most residential buildings.

The preferable solution to any elevated radon problem is to mitigate the incoming radon. For the case of soil borne radon this almost always entails the use of an active sub-slab depressurization system. For the case of water borne radon, particularly where large quantities of water are being used, aeration is the mitigation method of choice. Although the hatch houses have crude types of aeration systems in place for removal of nitrogen and oxygenation of water they are often located inside the hatch house. These systems are contributing to the radon/thoron exposure within the hatch house. For effective removal of waterborne radon/thoron these systems would need to be outside the enclosed structure. These engineered aeration systems can be quite costly to initially develop and install. Due to limited funding we decided to measure the employee personal exposure, over the work year to determine whether further remedial steps should be taken.

We do not know the exact proportion of Radon/Thoron exposure arising from the two potential sources; soil gas, and off-gassing from incoming water. We measured the cumulative exposure arising from potentially both sources in the hatch houses.

Materials and Methods

The ^{222}Rn and ^{220}Rn personal or area monitor was designed to measure radon and thoron in duplicate in order to estimate measurement precision. Two chambers have a diffusion barrier and inhibit thoron entry, two chambers permit both radon and thoron entry. Thoron is calculated by signal difference. A conducting foam, directly beneath the entry caps permit only radon or thoron gas passage. The monitor face is four lobed with length 5 cm. and thickness 1 cm. It is molded from electrically neutral ABS (CNi) plastic, i.e., plastic with embedded nickel coated carbon fibers.

The nuclear track film used for detection of the alpha particles is laser cut 9x9 mm square solid state nuclear track film (CR-39). The pristine film background is 5 to 15 tracks. Tracks over the entire film area are counted. The unit displays no charge artifacts and the calibration is constant in all situations. Using a video imaging system for track counting**, the efficiency for ^{222}Rn is (0.009 Track per Bq m^{-3} day) (0.32 Track per pCi/L day) and the lower limit of detection is 220 Bq m^{-3} day (6 pCi/L day). The efficiency for thoron is 0.013 Track per Bq m^{-3} day, (0.27 Track per pCi/L day) and the lower limit of detection is 1100 Bq m^{-3} day (30 pCi/L day).

After exposure, the CR-39 alpha track film is etched for 20 hours in 6 N KOH to reveal the alpha particle tracks as shallow pits. Track counting with image analysis and about 10 to 20% of samples are scored visually. Pristine nuclear track film and exposed positive controls are etched with each batch of field samples for Quality Control.

The hatchery personal that frequent the hatch house were each equipped with a radon/thoron dosimeter and instructed to wear the dosimeter during their time in the hatch house. They were also instructed to record the number of hours worked in the hatch house, the approximate water flow rate into the hatch house, and the condition of the building (windows open/closed). Dosimeters were worn only during hatch house work. When not in use, dosimeters were stored in the manager's office, which had previously been determined to be low in radon, with values of 52 Bq m^{-3} for facility C, 74 Bq m^{-3} for facility BS, and 37 Bq m^{-3} for facility B. Radon/thoron dosimeters were also placed in each hatch house (area monitors) during the year in order to determine the annual average radon and thoron concentration.

So as not to "saturate" the film of the dosimeters with high track counts they were all changed out on an approximate quarterly basis, this includes workers as well as the hatch house dosimeters. Table 1 shows the deployment schedule and the hatch house radon and thoron concentrations.

Previous radon measurements from the hatch houses did vary significantly depending on amount of water use in the hatch house and the amount of ventilation of the building. Facility B hatch house was measured using a continuous radon monitor for one week during May of 2000 and averaged 1000 Bq m^{-3}, with spikes to 2220 Bq m^{-3}, with the hatch house using 757 lpm of water. Facility BS hatch house was measured using a year-long Landauer alpha track detector and recorded an annual average of 640 Bq m^{-3}. Finally, facility C hatch house was measured via two short-term measurements; one in February 2001 with the hatch house using 227 lpm and the radon at 740Bq m^{-3}, and another measurement April 2001 at 1041 lpm showing 1480 Bq m^{-3}. This data does show that hatch house radon values are significantly elevated above U.S. Environmental Protection Agency guideline value of 148 Bq m^{-3}.

It should be pointed out that no previous thoron measurements were made in any of the facilities, either in the water or air.

Results

Table 2 below presents data on the cumulative exposure to all monitored users to the hatch house for each of the three facilities. Both a radon and thoron cumulative exposure is provided, in units of working level months (WLM). Our Radon/Thoron working level calculations assume an equilibrium ratio, Feq of 0.4 for radon and 0.02 for thoron. The radon and thoron decay product concentrations in Table 2 are in units of WL and WLM, so that published dose factors may be applied directly.

We had two choices for the calculation of the Radon/Thoron working level values; use the results from the dosimeters worn by each hatch house worker, or use the dosimeters that were left in place in the hatch house (area monitors) to monitor the hatch house concentrations and use employee occupancy time. We decided to use the area monitors because the hatch house reported exposure time from the personal dosimeters was small relative to total time deployed.

When not in use the personal dosimeters where stored in the managers office and this did not reflect the hatch house exposure.

Average radon concentrations in the three facilities seem consistent with previous measurement data with certain caveats. Facility B hatch house showed a week long average concentration of 1000 Bq m^{-3} measured in 2000, however, this was during water use and this facility does not use water to the same extent as the other two facilities. Figure 1 shows the details of water use for the three hatcheries over a one year period. Thus, this lack of water use throughout the entire year, which is the major source of the radon, explains why our current annual average is 270 Bq m^{-3}. The BS facility average annual value made in 1999 of 640 Bq m^{-3} is in reasonable agreement with the current value of 464 Bq m^{-3}. Finally, the 740 Bq m^{-3} for facility C measured in 2001 is consistent with our current value of 512 Bq m^{-3}.

Employee cumulative radon exposure from the three facilities shows a range from 0.186 to 0.001 WLM yr^{-1}. These values are all well below any currently established exposure limits for radon, where both the US EPA and the US Nuclear Regulatory Commission (NRC) have set a limit of 4 WLM yr^{-1}. The fish hatchery facility should technically be regulated by the Occupational Safety and Health Administration (OSHA); however, OSHA still uses 1970 vintage 10 CFR 20 ionizing radiation regulations, which reference 12 WLM yr^{-1} for radon exposure in the workplace. There is a wealth of radon concentration data for various building types and in various countries. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2000 report provides valuable data for concentration values. They show a geometric mean concentration for numerous countries around the world at 37 Bq m^{-3}. This value is similar to what the US EPA reports for the United States at 48Bq m^{-3} (EPA, 1992). Pennsylvania however, has much higher concentrations than the US and world-wide averages, with a basement average for the Commonwealth at about 263 Bq m^{-3} (Lewis, 2007). Our hatchery data is in line with the data for the Commonwealth with a range from 270 to 512 Bq m^{-3}.

Employee cumulative thoron exposure ranges from 0.0001 to 0.031 WLM yr^{-1}. The NRC and EPA exposure limit for thoron is 12 WLM yr^{-1}. The hatchery workers are well below this exposure limit for thoron. The world wide data for thoron concentrations in buildings and residences is much sparser. There are also more uncertainties associated with this data due to the various measurement techniques used, less effort devoted to quality assurance, and generally low concentrations are being measured. UNSCEAR 2000 quotes a range of equilibrium equivalent concentrations (EEC) of 0.2 to 12 Bq m^{-3} . See Appendix A for explanation of EEC. More recent data from 117 Winnipeg houses show a range from 5 to 297 Bq $^{m-3}$, with 60 of those homes below the detection limit (Chen, et. al., 2009). Our data above for the hatch house annual average falls within these ranges with values of 29, 53 and 113 Bq m^{-3}.

UNSCEAR (2000) adopts central values for the effective dose coefficient of 9 and 40 nSv per Bq m-3 hour for radon (EEC) and thoron (EEC) respectively (6.4 and 1.9 mSv/WLM respectively). The calculated dose is to target cells in bronchial epithelium implicated in bronchogenic carcinoma. Table 3 shows the calculated annual effective dose based on the hatch house area monitor measurements, the reported employee exposure time in Table 2 and the UNSCEAR dose factors.

Discussion

Employee exposure to both radon and thoron as measured in this study was surprisingly low, as compared to the available exposure limits set by EPA, NRC, and OSHA. These low exposures are likely due to the relatively short work times in the hatch house, combined with work during times of low radon concentration. Previous continuous radon monitor measurements (Lewis, 2001) showed very cyclic daily patterns to radon concentration, with lows around 2-5 PM and highs around 5-7 AM. This is consistent with Porstendorfer et. al. 1994 who found the highest activity during the night and early morning hours when the atmosphere was the most stable. At noon and early afternoon the mixing of the lower atmosphere is strongest and radon concentration is lowest. Finally, the low exposures are also due to building ventilation, when windows and doors are left open or ventilation fans are running.

Radon concentration measurements in fish hatcheries are sparse and to our knowledge no thoron measurements are available. Scott (1997) quotes personal dosimetry measurements for radon in two Ontario fish hatcheries ranging from 0.05 to 4.5 mSv yr^{-1} (10 mSv = 1 rem). This range of values is consistent with our Table 3 calculated doses for radon (0.003 to 1.03 mSv yr^{-1}).

Measurements of radon and thoron in this study show that estimates of decay product exposure and effective dose are well within occupational limits, ranging from 0.001 to 0.186 WLM for radon (4 to 1188 uSv per year) and 0.0001 to 0.031 WLM (0.2 to 58 uSv per year) for thoron.

Conclusions

Cumulative exposure to both radon and thoron made over one full year suggest that mitigation measures at this time are not necessary in these hatch house facilities.

If future modifications are made to the supply water that significantly increase radon and thoron concentration off-gassing or employee exposure time is increased, well designed aeration systems, outside the building structure should certainly be considered to further reduce radon/thoron concentrations in the supply water with a concomitant reduction in exposure. Repeat measurements during water use should be made at least annually along with employee time records to determine any changes.

The maximum effective dose values in the fish hatcheries studied were 1188 and 58 μSv per year for radon and thoron respectively We would urge other facilities to make similar long term baseline radon and possibly thoron measurements, even though our cumulative exposures are low. Other hatch house facilities in Montana, New York, Missouri, and Maine have already recorded indoor concentrations of radon in the hundreds of pCi L^{-1} with remediation required.

**The CR-39 film is etched overnight at NYU for 20 hours in 6N KOH along with pristine blanks and positive controls for QC. The tracks are counted with an Olympus SZ-CTV zoom microscope and tracks scored using Data Translation Global Lab Image software. About 20 percent of all films are scored visually as a QC measure using hard copy printout from a Minolta microfiche reader at 20X magnification.

Table 1. Radon and thoron concentrations measured in three Pennsylvania fish hatcheries over a one year interval

Facility	Time Period (dd-mm-yy)	Hatch House Average (Bq m^{-3})	
		Rn-222	*Th-220*
C	6-7-07 to 15-8-07 (30days)	603 +/-22	7 +/- 22
	6-9-07 to 10-12-07 (95 days)	362 +/- 22	15 +/- 7
	27-12-07 to 7-5-08 (132 days)	543 +/- 52	44 +/- 26
	13-5-08 to 6-8-08 (85 days)	595 +/- 41	N.D.
	Average +/- SEM	525 +/-56	22 +/- 11
BS	6-7-07 to 15-8-07 (30 days)	414 +/- 7	81 +/- 56
	6-9-07 to 10-12-07 (95 days)	344 +/- 181	167 +/-2
	1-1-08 to 7-5-08 (128 days)	492 +/- 85	81 +/- 11
	8-5-08 to 8-8-08 (93 days)	566+/- 26	N.D.
	Average +/- SEM	455 +/- 48	111 +/- 28
B	6-7-07 to 15-8-07 (30 days)	44 +/- 22	-85 +/- 0
	6-9-07 to 10-12-07 (95 days)	437 +/- 11	3 +/- 22
	21-12-07 to 7-5-08 (138 days)	204 +/- 118	118 +/- 2
	8-5-08 to 8-8-08 (98 days)	Missing	Missing
	Average +/- SEM	237 +/- 114	11 +/- 34

SEM= Standard error of the mean= S.D/√n

Table 2. Employee radon and thoron exposures measured over a one year interval in three Pennsylvania fish hatcheries

Facility	Employee	Hrs in HH	Rn WL	Rn WLM	Th WL	Th WLM
B	LD	275	0.0256	0.0413	0.0008	0.0013
	TE	12	0.0256	0.0018	0.0008	0.0001
	TH	72	0.0256	0.0108	0.0008	0.0003
	TW	49	0.0256	0.0074	0.0008	0.0002
	BM	4	0.0256	0.0006	0.0008	0.0000
B HH		Annual Average Radon Concentration is 237 Bq m^{-3}				
		Annual Average Thoron Concentration is 11 Bq m^{-3}				
BS	JV	412	0.0492	0.1192	0.0081	0.0196
	ZF	37	0.0492	0.0107	0.0081	0.0017
	NV	629	0.0492	0.1820	0.0081	0.0300
	DB	30	0.0492	0.0086	0.0081	0.0014
	JB	74	0.0492	0.0214	0.0081	0.0035
BS HH		Annual Average Radon Concentration is 455 Bq m^{-3}				
		Annual Average Thoron Concentration is 111 Bq m^{-3}				
C	CL	208	0.0568	0.0694	0.0016	0.0019
	MH	108	0.0568	0.0360	0.0016	0.0010
	KM	95	0.0568	0.0317	0.0016	0.0009
C HH		Annual Average Radon Concentration is 525 Bq m^{-3}				
		Annual Average Thoron Concentration is 22 Bq m^{-3}				

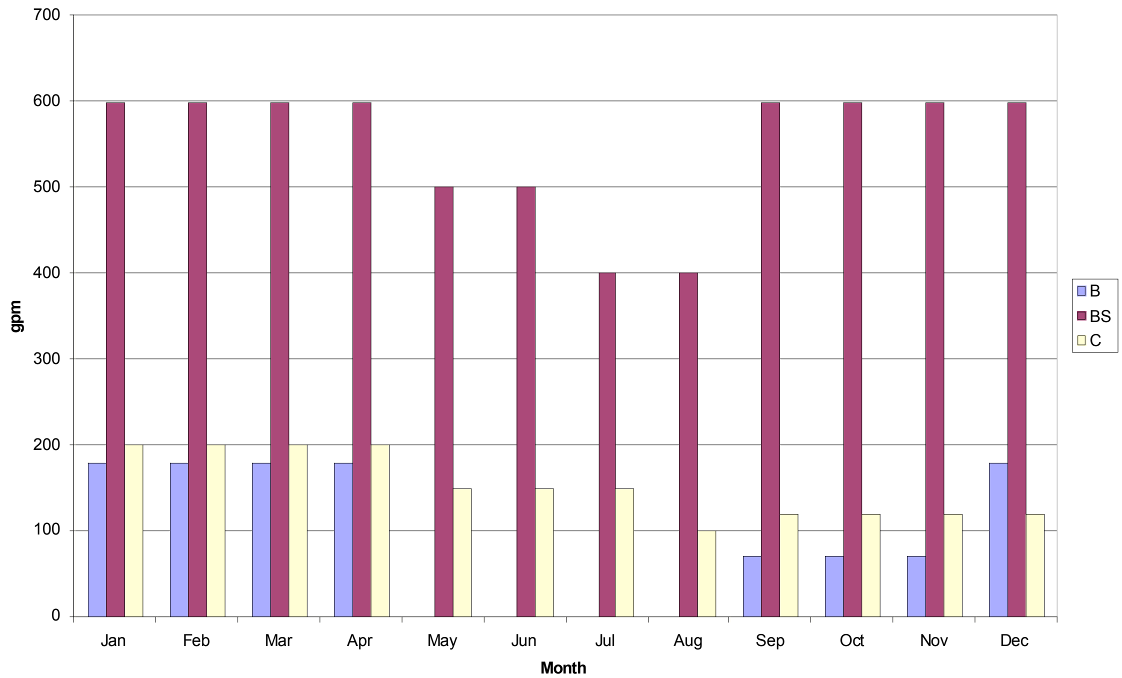
Radon WL equals (HH Avg. Rn x 0.4)/3700; Thoron WL equals (HH Avg. Th x 0.02)/274
WLM equals (Rn or Th WL x hrs)/170

Table 3. Employee annual effective dose in three Pennsylvania fish hatcheries

Facility	Employee	222Rn(μSv yr^{-1})	220Rn(μSv yr^{-1})
B	LD	234	0.006
	TE	10	0.003
	TH	62	0.017
	T	42	0.011
	BM	3.4	0.001
BS	JV	675	0.99
	ZF	61	0.09
	NV	1030	1.5
	DB	49	0.07
	JB	121	0.18
C	CL	393	0.1
	MH	204	0.051
	KM	180	0.046

1µSv = 0.1 mrem

Figure 1 Hatch House Water Use



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Appendix A

Equilibrium Equivalent Concentration (EEC)

The EEC is another way of expressing the radon (or thoron) progeny concentration in units of activity concentration, either Bq/m^3 or pCi/L. This term is more commonly used in Europe than the United States. By definition it is the concentration of radon in air, in equilibrium with its short-lived decay products which would have the same potential alpha energy concentration as the existing non-equilibrium mixture. Expressed mathematically it is:

EEC_{rn} = 0.104 C(Po-218) + 0.517 C(Pb-214) + 0.379 C(Bi-214)

Where the constants are the fraction of the PAEC (WL)
C = concentration of the three isotopes in Bq/m^3 or pCi/L

Also can be expressed as EEC = Rn Gas x ER, **or** EEC = Th Gas x ER

The dose is related to the working level (WL), but the WL is not the measurement of choice in residences and most other places because it requires real time equipment. Therefore, if we want dose but are measuring radon gas with passive detectors the EEC is important.