ORIGINAL ARTICLE

Radon levels in three fish rearing buildings at Cleghorn Springs State Fish Hatchery, Rapid City, South Dakota, USA

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Abstract

Fish hatchery workers may be exposed to potentially health-threatening radon gas liberated from ground water used during fish rearing. This study surveyed the radon levels in three fish rearing buildings (small tankroom, tankroom, and rearing pavilion) at Cleghorn Springs State Fish Hatchery, Rapid City, South Dakota, USA. Overall radon values ranged from below the detection limit in all three buildings to a high of 2,317.68 Bq/m^3 (62.64 pCi/L) in the tankroom. The pavilion had the lowest mean ± SE value of 56.57 ± 40.71 Bq/m^3 (1.23 ± 0.11 pCi/L), while the highest mean value of 796.21 ± 54.61 Bq/m^3 (23.67 ± 1.34 pCi/L) was in the small tankroom. Maximum radon levels were 1,231.36, 2,317.68, and 365.93 Bq/m^3 (33.28, 62.64, and 9.89 pCi/L) in the small tankroom, tankroom, and pavilion, respectively. Radon levels were significantly correlated with the number of tanks receiving water in both the small tankroom and tankroom, but no such correlation was observed in the relatively open-air pavilion. Even though the water at the hatchery was aerated outside, additional aeration from rearing tank spray bars inside the enclosed small tankroom and tankroom resulted in relatively high radon levels.

Keywords: *radon; fish hatchery; rearing*

Radon (^{222}Rn) is a colorless radioactive gas by-product of uranium decay occurring naturally in soil and bedrock (1–3). High radon levels are typically observed in groundwater associated with high-uranium substratum (4, 5). However, because of the low solubility of radon gas, it does not bind to water and is easily liberated through aeration (4, 6, 7). Thus, when water is aerated to remove gaseous nitrogen and increase oxygen at fish hatcheries, radon is liberated (2, 8). Within indoor areas, the liberated radon gas can accumulate, and long-term exposure is potentially hazardous to human health (3, 7, 9).

The negative effects of prolonged radon exposure on human health are well documented (3, 7, 9, 10). Radon is the second leading cause of lung cancer after smoking in the United States (11–14). The United States Environmental Protection Agency estimates that 21,000 lung cancer related deaths are caused by radon every year, with 2,900 of those in people who have never smoked (14). People who smoke are at a much higher risk of developing radon-induced lung cancer than people who do not (14).

In the United States, there are currently no federal regulations regarding acceptable radon levels for indoor environments (14–16). Guidelines from the United States Environmental Protection Agency recommend a maximum radon level of 148 Bq/m^3 or 4 picocuries/liter (pCi/L) (37 Bq/m^3 = 1 pCi/L) in the air (14). European member states have a maximum reference level of 300 Bq/m^3 (8.1 pCi/L) according to the 2013/59/Euratom Directive (17). Both maximum radon levels are based upon exposure durations, which impact potential cancer risk (9, 18).

Fish hatcheries frequently use large quantities of groundwater, elevating the risk of radon accumulation in fish rearing buildings or other areas where aeration occurs (2). High radon levels have been documented in a small number of studies, which examined radon in fish hatcheries. Flexser et al. (19) reported radon levels of 29,193 Bq/m^3 (789 pCi/L) and 24,679 Bq/m^3 (667 pCi/L) in the water of two spring fed ponds at a fish hatchery in Long Valley Caldera, California, USA. They did not test airborne radon levels, however. Dwyer and Orr (1) documented radon gas levels ranging from 7,400 to 9,250 Bq/m^3 (200–250 pCi/L) in a hatchery building. Kitto et al. (3) reported airborne radon levels as high as 2,997 Bq/m^3 (81 pCi/L) in a commercial fish hatchery. In a survey of radon levels in 12 fish hatcheries in the USA state of Pennsylvania, three hatcheries had airborne radon levels high enough to require mitigation (8). Indoor gaseous radon levels ranged from 636.4 Bq/m^3 (17.2 pCi/L) to 1,480 Bq/m^3 (40 pCi/L)

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at the three hatcheries, with an increase from 740 Bq/m^3 (20 pCi/L) to 1,480 Bq/m^3 (40 pCi/L) occurring when water flows were increased from 227 L/min to 1,041 L/min (8). Mitigation techniques, such as exhaust fans or relocating aeration from inside to outdoor locations, have been used to reduce indoor radon levels at fish hatcheries (2, 8).

The USA state of South Dakota owns and operates Cleghorn Springs State Fish Hatchery, a recreational fish hatchery in Rapid City. This hatchery produces fish in three distinct rearing buildings. Radon levels within these buildings have never been tested. This information is needed to determine if radon levels would require mitigation to protect the health of hatchery employees. Thus, the objective of this paper is to document indoor radon gas levels in three fish rearing buildings at Cleghorn Springs State Fish Hatchery, South Dakota, USA.

Materials and methods

This study was performed at Cleghorn Springs State Fish Hatchery, Rapid City, South Dakota, USA. Radon levels were recorded in three fish rearing buildings: the tankroom, rearing pavilion, and small tankroom (20; Figs. 1–4). Radon levels were measured using meters (Corentium Home, Airthings, Norway) with an accuracy/precision of 10% at 200 Bq/m^3 (21). One meter was located in each building (Fig. 5). Measurements were taken daily from 11 March 2020 to 11 June 2021 at approximately the same time each morning. In addition, the number of rearing tanks being used for fish production (with water flowing through them) was recorded daily. Because radon values were measured during actual fish production at the hatchery, as fish loadings changed throughout the year, the number of tanks being used fluctuated as well.

Tankroom

The tankroom contains 32 circular tanks for fish rearing. A range of 0–32 tanks were used for fish production during the 16-month study period (Table 1). It is a relatively-large, enclosed space at 23.0 m by 14.8 m, with concrete floors and ceramic block walls. The roof is prefabricated with concrete beams. All of the fiberglass circular tanks are above ground, with water flowing into each tank through a 5.08 cm-diameter spray bar. Each tank is 1.8 m in diameter and has a water depth of 76.2 cm. The spray bars are located 5.1 cm above the water level in the tank. Each spray bar is 61.0 cm long with 11 evenly distributed holes. These spray bars are set to a slight angle to keep water flowing in a circular fashion to make them self-cleaning (22). Water levels are controlled by an external standpipe, with one standpipe per tank. Each 7.6 cm-diameter standpipe is 66 cm tall and is contained in a 17.1 cm-diameter, 106.7 cm-tall housing, which is open on the top to allow for cleaning. There is no ventilation in the tankroom except when external doors are opened.

Rearing pavilion

The rearing pavilion is a relatively open-air building containing 32 in-ground tanks. A range of 0–32 tanks were used for fish production during the study period (Table 2). The building is 62.8 m by 37.3 m with a wall height of 3.0 m. The roof is peaked, with the peak falling 18.7 m from either wall. The floors are concrete, but the building is constructed of steel support beams and metal sheeting, with screen inlays along all walls for light and ventilation. The pavilion tanks are 6.1 m in diameter and 1.2 m tall, with operating water depths of 73.7 cm. The spray bar for each tank is 1.2 m long and 11.4 cm in diameter, with three discharge holes. Each spray bar is 10.2 cm above the water level, with water entering the tank at 5.1 cm above the water level. Every tank has an adjacent 16.5 cm-diameter 1.1 m tall standpipe located within an in-ground concrete cylinder that is 1.5 m in diameter and 1.7 m tall.

Small tankroom

The small tankroom is the smallest rearing building at Cleghorn Hatchery. It is only 6.0 m wide by 9.15 m long,

Fig. 1. Arial view of the Cleghorn Springs State Fish Hatchery. The three buildings (Small Tankroom, Tankroom, and Pavilion) included in this study are labeled with different icons.

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Fig. 2. Photograph of the tankroom at Cleghorn Springs State Fish Hatchery.

Fig. 3. Photograph of the small tankroom at Cleghorn Springs State Fish Hatchery.

with a ceiling height of 3 m. It has nine, 1.8-m diameter above-ground circular tanks resting on concrete floors with a drain system and standpipes similar to the tankroom. A range of 0–9 tanks were used for fish production during the study period (Table 3). This building has no ventilation except when the two external doors are open.

Effective radon dosage was calculated using the formula (23): Effective dose = radon level (Bq/m^3) × time × dose coefficient of 3 mSv per mJ h m^{-3} (24).

Data analysis

Data were analyzed using the SPSS statistical program (24.0, IBM, Armonk, NY, USA). In addition to descriptive statistics, regression and correlation analysis was used to examine any possible relationships between radon levels and the number of rearing tanks being used in each of the buildings. Significance was pre-determined at $P < 0.05$.

Results

Overall radon values over the course of this study ranged from below the detection limit in all three buildings to a high of 2317.68 Bq/m^3 (62.64 pCi/L) in the tankroom (Table 4). The pavilion had the lowest mean ± SE value of 56.57 ± 40.71 Bq/m^3 (1.23 ± 0.11 pCi/L), while the highest mean value of 796.21 ± 54.61 Bq/m^3 (23.67 ± 1.34 pCi/L)

Fig. 4. Photograph of the Rearing Pavilion at Cleghorn Springs State Fish Hatchery.

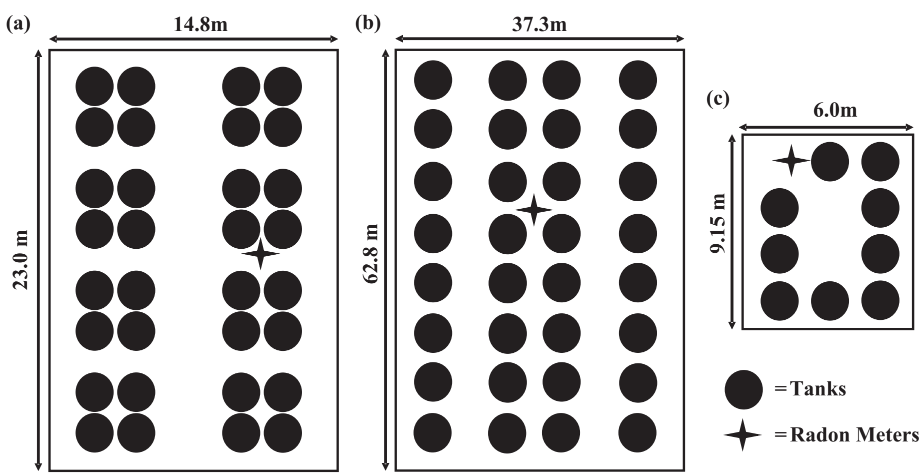

Fig. 5. Schematic of the (a) tankroom, (b) pavilion, (c) small tankroom at Cleghorn Springs State Fish Hatchery (not to scale). The point where radon readings were collected is marked with a four-point star, and tanks are marked with a black circle.

Table 1. The number of tanks receiving water, number of daily readings (N), and mean (± SE) radon values (both as Bq/m³ and pCi/L) for the tankroom at Cleghorn Springs State Fish Hatchery

Number of tanks	*N*	Radon	
		Bq/m³	pCi/L
0	16	94.28 ± 19.14	2.55 ± 0.52
21	23	356.84 ± 42.28	9.64 ± 1.14
22	1	123.95	3.35
28	5	166.94 ± 21.43	4.51 ± 0.58
29	12	210.22 ± 11.86	5.68 ± 0.32
30	20	204.17 ± 9.04	5.52 ± 0.24
31	2	246.24 ± 16.47	6.66 ± 0.45
32	37	442.95 ± 44.24	11.97 ± 1.20

Table 2. The number of tanks receiving water, number of daily readings (*N*), and mean (± SE) radon values (both as Bq/m³ and pCi/L) for the pavilion at Cleghorn Springs State Fish Hatchery

Number of tanks	*N*	Radon	
		Bq/m3	pCi/L
0	7	0.00 ± 0.00	0.00 ± 0.00
1	2	182.97 ± 182.97	4.95 ± 4.95
30	5	20.57 ± 8.32	0.56 ± 0.22
31	3	31.57 ± 8.80	0.85 ± 0.24
32	100	47.73 ± 3.45	1.29 ± 0.09

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was in the small tankroom. Radon levels in the tankroom were at intermediate levels between those of the other two buildings.

The number of tanks in production in each building varied from zero to maximum levels over the sampling period. Radon levels were significantly correlated with the number of tanks receiving water in both the tankroom ($R^2 = 0.132$; $P < 0.000$; Fig. 6) and small tankroom ($R^2 = 0.564$; $P < 0.00$; Fig. 7). However, there was no correlation ($R^2 = 0.002$; $P < 0.636$) between the number of tanks with flowing water and radon values in the pavilion (Fig. 8).

In all three buildings, radon levels were below 148 Bq/m^3 (4 pCi/L) when none of the tanks was receiving water. Radon levels generally stayed low in the relatively open-air pavilion regardless of the number of tanks with water. However, in the enclosed tankroom, particularly the small tankroom, radon levels increased as soon as water was flowing in any of the tanks.

There was no significant correlation between radon values and the time of year in the tankroom ($R^2 = 0.001$, $P = 0.739$), small tankroom ($R^2 = 0.008$; $P = 0.330$), or pavilion ($R^2 = 0.003$; $P = 0.582$).

Effective doses based on 2,000 h of worker contact per year, using mean radon levels for each building, ranged from a low of 0.63 mSv in the pavilion to a high of 12.08 mSv in the small tankroom (Table 5). Based on typical worker exposure in those buildings, effective doses dropped to 0.54 mSv in the small tankroom and 0.78 mSv in the tankroom.

Table 3. The number of tanks receiving water, number of daily readings (*N*), and mean (± SE) radon values (both as Bq/m^3 and pCi/L) for the small tankroom at Cleghorn Springs State Fish Hatchery

Number of tanks	*N*	Radon	
		Bq/m^3	pCi/L
0	24	131.66 ± 24.75	3.56 ± 0.67
6	5	760.94 ± 84.10	20.57 ± 2.27
7	27	771.55 ± 72.75	20.85 ± 1.97
8	58	1231.09 ± 49.86	33.27 ± 1.35
9	3	1085.83 ± 41.56	29.35 ± 1.12

Table 4. Mean (SE) and maximum radon readings (both as Bq/m^3 and pCi/L) from three buildings at Cleghorn Springs State Fish Hatchery ($n = 116$ for tankroom and $n = 117$ for pavilion and small tankroom)

Location	Bq/m^3		pCi/L	
	Mean ± SE	Maximum	Mean ± SE	Maximum
Tankroom	294.50 ± 20.43	1231.36	8.06 ± 0.57	33.28
Small tankroom	875.60 ± 49.70	2317.68	23.67 ± 1.34	62.64
Pavilion	45.61 ± 4.23	365.93	1.23 ± 0.11	9.89

Minimum values for all three buildings were below detection limits.

Discussion

The results of this study indicate that with the number of tanks in operation and hatchery employee exposure times, radon levels in the tankroom and small tankroom are high enough to justify remediation. The maximum radon levels of 1,221 Bq/m^3 (33 pCi/L) and 2,331 Bq/m^3 (63 pCi/L) for the small tankroom and tankroom, respectively, both exceed the 148 Bq/m^3 (4 pCi/L) and 300 Bq/m^3 (8.1 pCi/L) recommended maximum levels by the USA and European Union (14, 16, 17). In addition, the mean value of 888 Bq/m^3

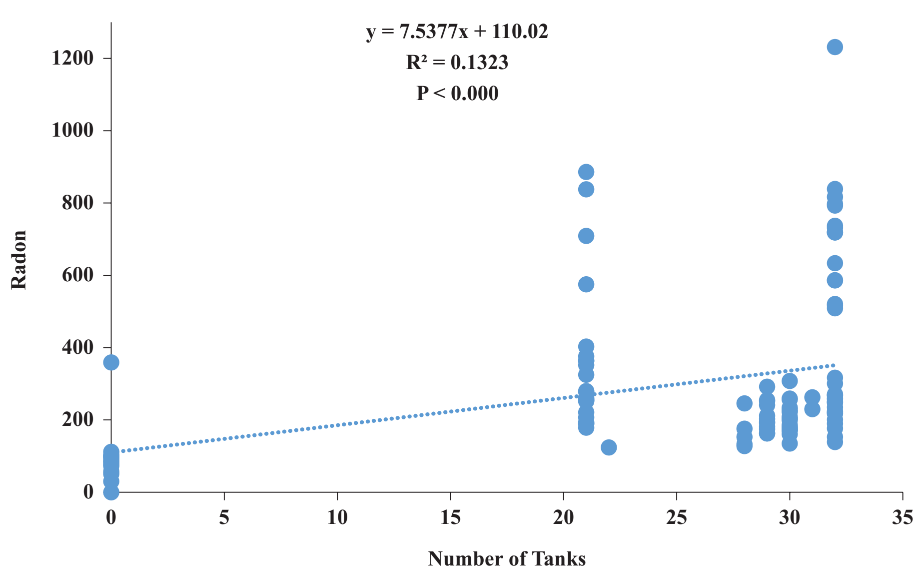

Fig. 6. Radon readings (Bq/m^3) in relation to the number of tanks with flowing water in the tankroom at Cleghorn Springs State Fish Hatchery.

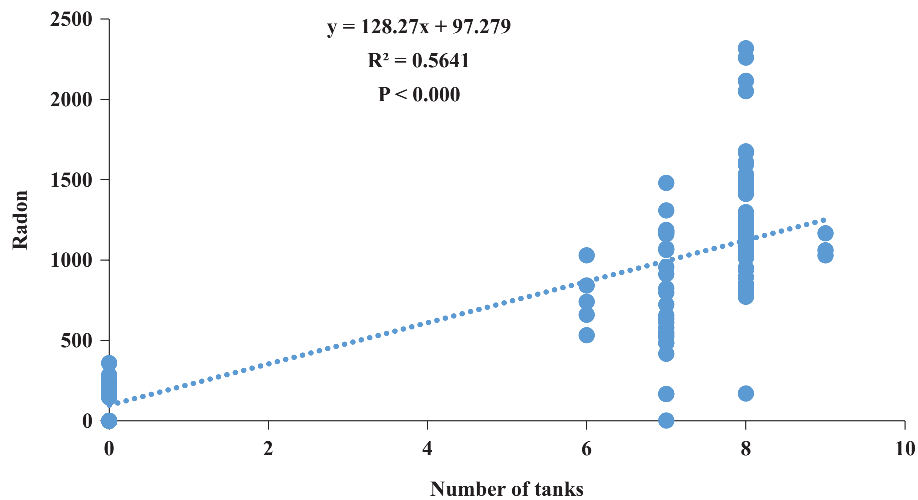

Fig. 7. Radon readings (Bq/m³) in relation to the number of tanks with flowing water in the small tankroom at Cleghorn Springs State Fish Hatchery.

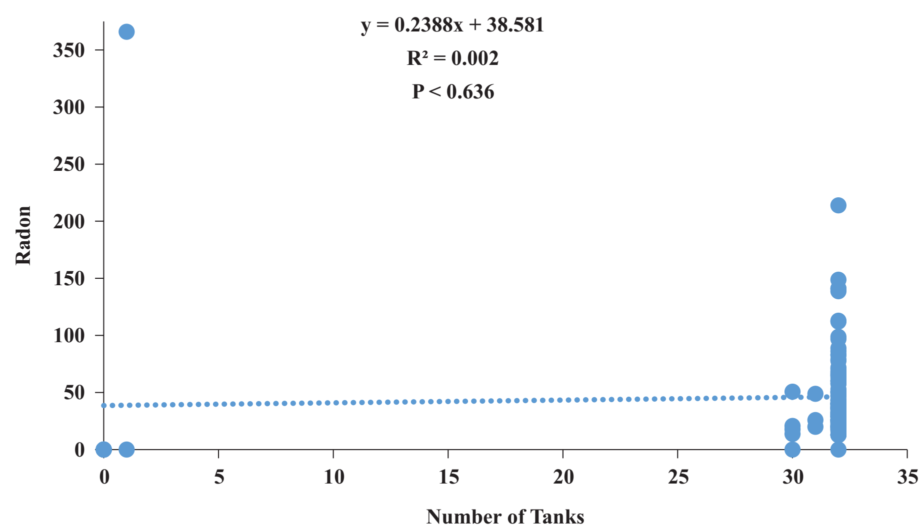

Fig. 8. Radon readings (Bq/m³) in relation to the number of tanks with flowing water in the pavilion at Cleghorn Springs State Fish Hatchery.

(24 pCi/L) in the tankroom was higher than the recommended maximum levels as well. However, despite these relatively high radon levels, current management practices at Cleghorn Hatchery result in very short radon exposure times for employees in the tankroom and small tankroom, likely lowering the need for intense mitigation (23, 25). Hatchery employees are typically only in the small tankroom for a few minutes each day to fill feeders or clean tanks. Feeding and cleaning in the larger tankroom takes less than an hour. However, there are limited occasions, such as moving fish, tagging, or other activities, when hatchery staff spend most of the day in the tankroom. Because these buildings are currently enclosed with no ventilation, it is likely that installing an exhaust fan or ventilation system would dramatically reduce radon levels, further reducing the risk in addition to current low exposure times for hatchery staff (25–30).

The radon levels observed at all three of the Cleghorn Hatchery rearing buildings were much less than those reported for other fish hatcheries. Indoor levels as high as 22,200 Bq/m³ (600 pCi/L) were reported for a fish hatchery in the state of New York, USA (2). Dywer and Orr (1) documented radon levels of 7,400–9,250 Bq/m³ (200–250 pCi/L) in hatchery rearing buildings with inadequate ventilation. In contrast, a report on 12 fish hatcheries in Pennsylvania reported that only three of the 12 hatchery locations showed radon levels above 148 Bq/m³ (4 pCi/L) (8). Differences between hatchery building radon levels may be because of differences in soil uranium concentrations, types, and locations of water

Table 5. Effective doses (mSv) for three buildings at Cleghorn Springs State Fish Hatchery, based on mean radon levels at theoretical maximum exposures (2,000 h per year) and typical current exposure times of 1 h, 30 min, and 2 h for the tankroom, small tankroom, and pavilion, respectively

Location	Effective Dose (mSv)	
	Theoretical (2,000 h)	Typical
Tankroom	4.15	0.54
Small tankroom	12.08	0.78
Pavilion	0.63	0.16

aeration, building construction, and building ventilation (30–33).

Compared to the tankroom and small tankroom, the pavilion radon levels were much lower. This is easily explained by the continually open screened ventilation encompassing nearly the entire perimeter of the building. Any radon gas liberated during rearing tank spray bar aeration immediately dissipates into the atmosphere (34).

The significant correlations between the number of tanks with flowing water and radon levels in the tankroom and small tankroom clearly indicate the liberation of radon from ground water via aeration (6, 35). Even though the aeration canisters for Cleghorn Hatchery are located outside, external to all of the hatchery buildings, the aerated water still contains radon (6, 36, 37). When this water is dispensed from the tank spray bars, further aeration occurs, and additional radon is liberated (6). Similarly, Lewis (8) also observed large increases in indoor airborne radon levels with increased water flows in a hatchery rearing building.

As a practical matter, the results of this study indicate that indoor areas where hatchery staff would likely spend considerable time, such as offices, laboratories, or other work rooms, should not be located in the same building as fish rearing units if radon levels are of concern. With the significant impacts of radon exposure on human health (1, 4, 7, 9–13), simply avoiding high-radon work areas is likely a more effective and less-expensive remediation technique than conducting more intense radon remediation at Cleghorn Springs State Fish Hatchery.

Conclusion

This is the first study to examine radon gas levels in a fish hatchery in South Dakota, USA. During fish production, radon gas levels in the tankroom and small tankroom buildings at Cleghorn State Fish Hatchery are over the recommended maximum of 148 Bq/m^3 or 4 picocuries/liter (pCi/L) (37 Bq/m^3 = 1 pCi/L) (3, 14, 16). However, radon levels in the more open-air pavilion are typically well-below levels of concern. Depending on hatchery staff exposure durations, which currently are minimal, remediation may be needed within the tankroom and small tankroom. Continuing to limit staff time in the tankroom and small tankroom at Cleghorn Hatchery is recommended. In addition, the current practice of housing offices, shop, and conference area in buildings separate from fish rearing structures should also continue.

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Conflicts of interest and funding

The authors declare no potential conflicts of interest and no external funding.

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