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RADON REMOVAL FROM DRINKING WATER USING GRANULAR ACTIVATED CARBON, PACKED TOWER AERATION AND DIFFUSED BUBBLE AERATION TECHNIQUES

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ABSTRACT

The study is part of an EPA-funded Cooperative Agreement on radon removal for small public water supplies. The granular activated carbon (GAC) units operated for 478 days with an average radon removal efficiency of 81.1 ± 7.7%. Cores of the GAC indicated that it was contaminated with enough radium-226 and uranium-238 to be considered as a low level radioactive waste. Additionally, the operating GAC units emitted substantial amounts of gamma radiation. The packed tower system consistently removed 90 to 99% of the radon, with better removals (97 to 99%) occurring using mini and pall rings as media. Increasing the air:water (A:W) ratio above 2:1 to 5:1 had little impact on removal efficiency. The diffused bubble system removed 90.5 to 99% of the radon at A:W ratios of 5:1 to 15:1. Both aeration systems released significant amounts of radon (2,000-20,000 pCi/L) into the air and also had potential problems with precipitation of iron and manganese and bacteria fouling.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

Radon (Rn) is a colorless, odorless and tasteless radioactive gas which can dissolve into groundwater in uranium-containing bedrock. Concern about radon contamination has increased as recent risk assessments by the Environmental Protection Agency (USEPA) and the National Academy of Sciences have indicated that inhalation of radon may result in 5,000 to 20,000 lung cancer deaths per year in the United States. Although radon is primarily considered an indoor air pollutant, it becomes a problem in water when it is released into the air during water use.

Though no standard for radon in drinking water is currently available, the USEPA is expected to release a proposed limit during 1988. Treatment alternatives must be included as part of the proposed regulations. The results presented in this paper are part of a USEPA-funded Cooperative Research Agreement (WERL; Cincinnati, Ohio) to evaluate radon removal efficiency, safety and economics of three treatment techniques: Granular Activated Carbon (GAC) Adsorption, Packed Tower Aeration and Diffused Bubble Aeration. The research focuses on radon removal for small public water supplies because many of the communities which will be affected by the radon regulation have flows less than 20,000 gpd. These communities will need low cost/low maintenance systems with the ability to handle fluctuating loading conditions.

METHODS AND MATERIALS

GAC SYSTEM

The GAC system tested was located at the Rolling Acres Mobile Home Park in Mont Vernon, N.H. (Average flow (Q) = 10,681 ± 3,164 gpd, Average Influent Rn = 191,113 ± 63,093 pCi/L). The system, designed by Lowry Engineering (Unity, Me), consisted of 2 filters operating in series. The first filter (30 in. diameter) contained 20 ft^3 of Barneby Cheney 1002 coconut-based carbon. The second filter (36 in. diameter) contained 27 ft^3 of carbon. During this project, the system was monitored for 478 days and it continues to supply water to the park's homeowners. Results of the first 4 months of operation (October 1986-February 1987) were reported at the 1987 AWWA Conference (1).

Raw water from two bedrock wells passed through two atmospheric storage tanks and a pressurization system before entering the GAC units. The system was designed with the capacity for backwashing each GAC unit separately. Taps were installed in each filter so that water passing through could be sampled discretely as a function of depth (Filter #1: Top port at 6 in. depth, Ports 2-5 at 15, 24, 33, 42 in. depths, respectively; Filter #2: Ports 6-10 at 9 in. intervals with depth). Water samples of the influent, effluent and from individual ports were analyzed for radon, pH, alkalinity, turbidity, uranium (U), radium (Ra), iron (Fe), and manganese (Mn). Dissolved oxygen, microbial numbers and temperature were only monitored in the influent and effluent. Flow through the units and gamma exposure rates were also monitored during each sampling session.

Special sampling events were conducted to assess the GAC system's response to normal diurnal flow variations and backwashing. Diurnal sampling was conducted on two consecutive days for periods of 12 hrs each (0800 to 2000 hr). Samples for radon analysis were taken at all ports and of the influent and effluent. The filters were backwashed separately for 10 minutes after 477 days of operation. The backwash rate originally specified with the design was 5 gpm/ft^2, however, this rate resulted in substantial loss of GAC from the first filter so it was curtailed to 2.04 gpm/ft^2 (10 gpm) within one minute and remained at that level for the rest of the backwashing. Filter #2 was backwashed at a rate of 1.41 gpm/ft^2 (10 gpm). Radon samples were taken of the influent, effluent and from all ports before backwashing and at 1.3, 2.6, 3.9 and 24 hrs after backwashing. Samples for temperature, alkalinity, turbidity, pH, Fe, Mn, U and Ra were collected from the influent, effluent and ports 1,3,5,6,8 and 10 before backwashing and after 1.3 and 24 hrs. Backwash water samples were collected for radon, U, Ra, Fe and Mn.

The GAC media in the filters was cored after 295 days of operation. Composite samples of the media from the top, middle and bottom of each filter were analyzed for U and Ra. Analyses for Fe, Mn and heterotrophic bacteria were also conducted on the GAC samples. A narrow diameter (1 in. I.D.) plexiglass coring tube was inserted into each tank through an opening in the top while a very small amount of backwash water slightly fluidized the bed. Two cores were taken from each filter and composited to obtain enough material for analysis.

PACKED TOWER SYSTEM

The packed tower system tested was designed by Northeast Environmental Products (Lebanon, NH) and installed at the Mont Vernon site. The 18 ft tall tower was 1 ft in diameter and was constructed of stainless steel. Water was pumped directly from the wells to approximately 6 in. above the packing and sprayed over the plastic media with a nozzle. Air, supplied by an industrial blower, entered the tower 0.5 ft below the media. Off-gas from the tower was released directly into the atmosphere. Treated water was collected in a 13.2 gallon reservoir, located below the media, where it was held until pumped to the atmospheric storage tanks.

Water samples were collected of the influent and effluent as well as from 3 stainless steel sampling ports located 1.5, 6.5 and 12.5 ft below the influent nozzle. Plastic tubing conveyed the water from the sampling ports to the sampling board below.

The packing media tested were Glitsch[R] mini-rings and saddles and Koch[R] pall rings. The overall packing height was 12.3 ft for both of the Glitsch media and 11.8 ft for the Koch media.

Several 3 hr runs were conducted at air:water (A:W) ratios of 20:1, 10:1 and 5:1 and high (4.25-17 gpm) and low (0-7 gpm) flow conditions. (The fluctuation in water flow was a function of the variable yield of the wells at the site).

Water samples for influent, effluent and from all ports were taken for radon. Alkalinity, turbidity, Fe, Mn, and temperature analyses were conducted on the influent and effluent. Samples were collected after 15, 30, 60, 120 and 180 minutes of operation.

DIFFUSED BUBBLE SYSTEM

The diffused bubble system tested was designed by Lowry Engineering (Unity, Me). It consisted of 3 polyethylene tanks (capacity 270 gallons each) operating in series. Aeration was provided by a blower which delivered air to spiral plastic tube diffusers (0.75 in. diameter) containing numerous 15/1000 in. diameter holes and located 14 in. above the tank bottom. Water was pumped directly from the wells to a pumphouse located at the Scobie Pond Housing Development (Derry, NH) (Rn_{ave} = 77,477 ± 6,512 pCi/L; Q_{ave} = 9,965 ± 346 gpd). Water flowed through each tank and finally into an atmospheric storage tank. Samples of the influent to each of the tanks and of the effluent from tank 3 were obtained directly from sampling valves. Off-gas from the tanks was collected in a common pipe and vented to the outside of the building.

Experiments consisted of a number of runs at various A:W ratios (2:1, 3:1, 5:1, 7:1, 10.5:1 and 15:1) and two water flowrates (12 and 27-33 gpm). During each run, the system was operated for 2.5 detention times. Samples were analyzed for radon (all ports) and alkalinity, turbidity, Fe, Mn, and temperature (influent and effluent only) after 0, 15, 30, 60 and 120 minutes of operation.

ANALYTICAL TECHNIQUES

Radon was analyzed according to the method specified by Pritchard and Gesell (2) and USEPA (3) as modified at UNH (4). U and Ra on the core samples were analyzed by the NH Department of Public Health using a gamma spectrometer equipped with a Ge/Li detector. GAC core samples were dried to a constant weight in 8 oz. mason jars. They were subsequently capped and stored for 44 days. Each sample was counted for 10 hours using a ^{234}Th series library. Gamma exposures were measured at several locations within the Mont Vernon pumphouse and on the surface of the GAC units (top, middle, bottom) using a survey meter equipped with a gamma/beta detector. Personnel exposure was monitored using dosimeter badges and finger rings. Off-gas radon activities were measured using a Pylon AB-5 radiation monitor.

Only results for the radon and other radionuclide analyses will be reported in this paper because of space limitations. Results of all other analyses will be available in the final project report which will be completed in 1989.

RESULTS AND DISCUSSION

GAC SYSTEM

As reported at the 1987 AWWA Conference (1) during the first 120 days of operation the GAC profiles were similar to those expected except that the effluent radon levels were much higher than anticipated by the design. The cause of the problem was a combination of high flowrates and high influent radon activity resulting in an overall increase in radon loading in the GAC units over the design specifications.

This trend continued for most of the operating period. The flowrate to the GAC units was approximately 25% greater than anticipated in the original design. During Summer 1987 there were test periods where the flowrate through the units was as much as 74% above design. Compounding the problem, the influent radon activity also remained above design levels for much of the operational period. However, in Fall 1987, a new well began serving the community which had an average radon activity of 61,584 ± 8,692 pCi/L. The resulting loading rate of radon to the GAC units (Fig. 1a) was considerably higher than the design value of 3.81×10^9 pCi/d except for a short period during the end of the experiment when the influent radon activity decreased markedly.

It is not surprising that effluent radon activity was considerably greater than that predicted by the design (Fig. 1b) and by other researchers (5). Though the overall radon removal only averaged 81.1 ± 7.7%, the GAC units retained much more radon than anticipated in the design (Fig. 1c), except during the last part of the experiment when loading decreased concomitantly. There was a strong linear correlation (Fig. 1d) between the radon adsorbed by the GAC and the radon applied. During the last 100 days of operation, the decrease in radon applied and retained was not reflected in a concurrent decrease in the effluent radon activity. It is possible that fouling of the GAC by bacteria, Fe, Mn or organics may have depleted some of the adsorption capacity of the GAC.

During the diurnal flow variation studies there was no significant difference ($\alpha = 0.05$) over the 12 hr sampling periods in percent removal (Day 1 = 80%; Day 2 = 75%) in spite of flow variations of 5.7 to 13.0 gpm. Influent radon activities remained fairly constant over the 12 hr sampling periods, but were significantly different ($\alpha = 0.05$) on the two days the experiments were conducted (Day 1 = 190,115 ± 3,813 pCi/L; Day 2 = 163,388 ± 11,320 pCi/L). The GAC units appeared to respond consistently to daily variations in flow, influent radon activity and loading indicating that they will produce a stable effluent quality over diurnal periods.

The backwashing had no appreciable effect on radon removal. It remained in the range of 72 to 78%. This was expected as previous researchers had reported that backwashing had little impact on effluent quality (5). In GAC #1 there was no significant difference ($\alpha = 0.05$) in the radon content of the backwash water over the 10 minute flushing period. In GAC #2, however, there was a slight improvement with time (Sig. Diff. at $\alpha = 0.05$, Not Diff. at $\alpha = 0.02$).

The backwash water from GAC #1 was highly colored (red-brown) and contained numerous particulates. Even after the prescribed 10 minute backwash period, the water was still murky. The initial backwash water from GAC #2 was also slightly colored (red-brown) and turbid, but was flowing clear after the 10 minutes of backwashing.

Though the backwashing event appeared to have little effect upon the radon removal efficiency of the GAC units, it did seem to remove potential fouling contaminants, especially in GAC #1. The problem of fouling could become important in operation of GAC units serving communities using groundwater supplies containing organics, particulates, Fe, Mn or bacteria.

The results of the GAC coring are summarized in Table 1 and are based on the assumption that the GAC had a bulk density of 428 kg/m^3 (dry weight). The data indicate that the GAC exceeded the de minimus levels for ^{226}Ra through both filters. Contamination above the de minimus standards means that the material is considered a low level radioactive waste (LLW). GAC #1 and the top of GAC #2 also exceeded the de minimus level for ^{238}U. None of the GAC was significantly contaminated with ^{235}U. ^{210}Pb measurements will be performed during Summer 1988.

The GAC from both units is currently considered by the State of New Hampshire to be a LLW because it exceeds the de minimus levels for ^{226}Ra. As a result, it must be shipped to an approved LLW landfill in the western United States. Current estimates predict that the cost of dewatering, stabilization in concrete, transportation and disposal by a certified company will be approximately $13,000 to $15,000 for the 47 ft^3 of GAC at the Mont Vernon site. It is not clear whether the levels of contamination adsorbed to the GAC would be high enough to render it a LLW in other states. Influent levels of uranium in the Mont Vernon raw water averaged 24.2 ± 4.2 pCi/L. Levels of radium, however, were substantially lower, rarely above 1-2 pCi/L. Because of the affinity of the GAC for adsorbing trace amounts of these radioactive contaminants and because of their long half-lives, the GAC may become significantly contaminated with them which presents disposal problems if the GAC needs to be replaced.

As observed during 120 days of operation (1), the beta and gamma radiation exposure continued to be significant. Levels at the surface of the tanks decreased somewhat after coring and remained low because of the decrease in radon loading to the GAC. Levels ranged from 16 mR/hr in the top of GAC #1 to 1.8 mR/hr in the bottom of GAC #2, a significant decrease from the values observed earlier of 40-46 mR/hr and 6-11 mR/hr, respectively.

The data imply that the GAC units were emitting substantial amounts of gamma radiation. In a new computer program to predict the probable dose of gamma radiation from the ^{214}Bi and ^{214}Pb progeny of radon accumulated in GAC filters, Keene and Rydell (6) assert that the 1/10 permissible unrestricted area occupational gamma exposure is 0.2 mR/hr. The exposures resulting from the Mont Vernon GAC could be considerably higher than the 0.2 mR/hr level, indicating that shielding may be necessary as a minimum precaution.

The sampling team for the project routinely wore film dosimeter badges which indicated that the personnel were never exposed to detectable amounts of gamma radiation during routine sampling. During the coring event, however, the badges all registered exposure. The coring required approximately 1-1.5 hrs of direct contact with the filters and resulted in exposures of 40-100 mREM. (400 mREM is the maximum monthly allowable exposure for a worker in the nuclear industry.) These data corroborate radiation monitoring conducted with the survey meter and indicate that gamma exposure is a significant concern for operators involved with GAC maintenance.

PACKED TOWER

After approximately 15 minutes, the packed tower system was operating at steady state conditions which is typical of towers with short retention times. As a result, all of the data collected at 15 minutes and later were pooled for use in statistical analysis. Duncan's multiple range test was used to compare the radon removals obtained with different packing material. In all cases, the saddles provided significantly ($\alpha = 0.05$) lower removal than the mini or pall rings. In 50% (3 of 6) of the cases , the mini and pall rings showed no significant difference in removal (Fig. 2). At high flow (A:W = 5:1) and low flow (A:W = 5:1 and 20:1), the removal with the mini rings was significantly higher than that attained by the pall rings. These differences, which ranged from 0.6 to 1.1%, may be attributable to variations in liquid loading to the tower or to the fact that the mini rings were packed to a depth of 12.3 ft, while the pall ring packing was only 11.8 ft deep. The flow from the wells was highly variable on days when the mini rings were being used and may have decreased the liquid loading to the tower, resulting in an increased removal efficiency during these runs. Due to fluctuations in well yield, no conclusions could be drawn concerning the effect of flowrate on percent radon removal.

The top section (0.5-1.0 ft) of packing removed significantly ($\alpha = 0.05$) more radon than the lower portions of the tower (Fig. 2). Radon removal in the top section of packing could not, however, be solely attributed to the media. Other studies (7) have shown that spraying water through a nozzle can remove up to 70% of the radon dissolved in water. In all cases, the lower 6 ft of packing accounted for a very small percentage of radon removal. With the mini rings, which were densely packed, but allowed uniform water flow, most of the removal occurred in the top 1 ft of packing. The slightly lower removals observed with the pall rings probably resulted from the smaller depth of the top section (0.5 ft). The saddles, which appeared to restrict water flow to some extent, had a slightly lower percent removal than both types of rings in the top 1 ft section.

Overall, the packed tower data indicated that the removal of radon was consistently in the range of 90 to 99%, the better removals (97 to 99%) occurred with the mini and pall rings. These are similar to the removals predicted by Cummins (8). The radon removals observed for the saddles (90-94%) may have been lower than the other media, because the saddles appeared to restrict water flow and reduce turbulence. Typically, removals of 58-78% occurred as a result of the combined action of spraying and turbulence through the first 0.5 to 1 ft of packing. After falling through 6 ft of packing the total removal was 90-93%. The data imply that effluent activities below 1,000 pCi/L may be difficult to attain using the packed tower if the raw water contains 100,000 pCi/L or more of radon. Though the percent removals observed decreased as the radon activities decreased with depth in the tower, greater removals may still be possible. Further research needs to be conducted to address how to best maximize removal in water with lower radon activities.

The data suggest (Fig. 2) that A:W ratios of 5:1, 10:1 and 20:1 achieved similar maximum radon removal efficiencies. There was a slight decrease in the removal at an A:W = 2:1 (97%), while A:W = 1:1 yielded significantly lower removal (87%). The data imply that increasing A:W above the level of

2:1 to 5:1 in the packed tower tested had little impact on removal efficiency, while significantly increasing capital and operational costs.

Radon activities in the off-gas from the packed tower ranged from 2,410 to 21,200 pCi/L. [These activities are 100 times greater than those reported at the 1988 AWWA Conference (Orlando, Fla) because of an error in the conversion (cpm→pCi/L) equation initially used]. Though the data were somewhat variable, because of the fluctuations in water flow to the tower, radon activity in the off-gas generally increased with decreasing A:W ratios. This trend was expected because the amount of radon transferred from the water to the air was fairly constant while the volume of air through the tower increased with increasing A:W ratios. The average outdoor level of radon of 0.2 pCi/L (9) is two to three orders of magnitude below that exiting the packed tower. Data was not collected to determine whether the plume of radon leaving the tower was adequately diluted before reaching the ground. Because radon is considerably more dense than air (9.73 g/l at 1 atm and 0°C), on calm days sufficient dilution may be difficult to achieve before off-gas sinks to the ground. Further studies should include air monitoring around the tower to evaluate this phenomenon.

The packed tower was run on 3 separate days for periods of 6 to 8 hrs using A:W = 2:1 and pall rings. Though these studies were run in the winter when air and water temperatures averaged 14.2 ± 2.8°C and 7.0 ± 2.2°C, respectively, radon removals remained high (97.4 ± 0.4%). The results of the daily runs compared favorably with those obtained during the 3 hr experimental runs (96.9 ± 0.5%). Temperature seemed to have little effect on removal as seen from the fact that there was no significant difference (α = 0.01) between the daily continuous runs and the 3 hr experiment.

The major operational problems with the packed tower appear to be the potential health hazard from the off-gas, fouling of the packing media by Fe, Mn or bacteria and freezing of equipment. The Mont Vernon tower was enclosed in a wooden structure which channeled cold air down into the building causing the PVC pipes to crack, even though they did not have water in them. In northern climates, provisions would need to be made to insure that piping be insulated or placed in a warm area to prevent freezing, especially during the night when demand for water may be low or non-existent. In addition, if temperatures were low enough, water flowing through the tower might freeze causing clogging.

DIFFUSED BUBBLE SYSTEM

Fig. 3 shows the radon removals obtained at each A:W ratio and water flowrate tested for the diffused bubble system. For most conditions, it had reached a steady state after 30 to 60 minutes of operation. As A:W ratios increased there was a statistically significant increase (α = 0.05 and 0.01) in the percent radon removal attained (Fig. 3). We are currently running tests with A:W ratios greater than 15:1 to determine the maximum radon removal possible with this diffused bubble system. The removals obtained at the low water flowrate (for a given A:W ratio) were always significantly (α = 0.05 and 0.01) better than those obtained with the high flowrate, except at

A:W = 2:1 and 3:1. The greater removal capacity at the low water flowrate was probably a result of the longer hydraulic detention time. However, at the lowest A:W ratios (2:1 and 3:1), with the low water flowrate, the air flow (<5.0 cfm) was so small that the bubble distribution was severely limited, resulting in less radon removal. Higher A:W ratios showed increasingly less difference between the removal obtained with the two water flowrates. Under these conditions, the air flow for the high water flowrate appeared to be great enough to compensate for the difference in hydraulic detention time.

The percent radon removal from tank 3 was much greater than from tank 1 (Fig. 4). As the A:W ratio increased, the efficiency in the first tank increased. When A:W ratios were 5:1 or greater, 39 to 76% of the radon was removed in the first tank. At the low A:W ratios the slightly lower elevation of the first tank (approximately 1 cm) resulted in a reduced air flow which decreased the radon removal. In initial testing with the diffused system (10) at this site, differences in diffuser elevation caused the same atypical removal pattern to occur at low A:W ratios in tank 1 and at all A:W ratios in tank 2. The results indicated that equal tank and diffuser elevations in the small community multiple tank systems is crucial to achieving optimum radon removal.

When operating at A:W ratios of 5:1 and greater (at both high and low flow), the overall radon removal from the diffused bubble system ranged from 90.6 to 99.0% with effluent activities in the range of 700-6,512 pCi/L. However, even with removal efficiencies of 98%, it would be difficult to produce effluent radon activities of 1,000 pCi/L if the raw water contained more than 50,000 pCi/L using the system as designed.

In previous work with small diffused bubble systems, Lowry (11) obtained up to 99% removals at A:W ratios of 3.4:1 and aeration periods of 60 minutes. The results obtained in the Scobie Pond continuous flow unit at aeration periods of 22 to 68 minutes indicate that diffused bubble aeration may be an adequate treatment technique provided that the influent radon activity is not excessive.

As observed with the packed tower, the radon activity in the off-gas from the diffused bubble system increased as the A:W ratio for a given water flowrate decreased. Radon activities in the off-gas ranged from 4,167 to 18,600 pCi/L. [These activities are 100 times greater than those reported at the 1988 AWWA Conference (Orlando, Fla) because of an error in the conversion (cpm→pCi/L) equation initially used]. The diffused bubble system will have the same problem with dilution of the plume as experienced with the packed tower.

The diffused bubble system was used for 29 days to treat the water supply used by the community, operating at an A:W = 10.5:1. The typical water flowrate through the system during the period was 27 to 33 gpm. In most cases, the wells pumped water through the diffused bubble system for periods of 35 minutes or less. The blower was set to operate for 8 minutes after the wells stopped pumping raw water to the tanks. The diffused bubble system removed an average of 97.6 ± 0.35% of the influent radon dissolved in the raw water. The results were in agreement with those obtained during the 2 hr experimental run (97.4% removal) at high flow and A:W = 10.5:1. The majority of the radon was removed in the first tank (67.8 ± 4.3%). The major concerns with the diffused bubble system are the potential for off-gas health hazards and possible precipitation of Fe and Mn within the system.

CONCLUSIONS

All of the systems tested were successful at removing radon from drinking water. The GAC system achieved the lowest percent removals (81.1 ± 7.7%), while both of the aeration techniques were capable of 97-99% removal. Some of the problem with the GAC system was a result of overloading, but even when the system was loaded at design levels, radon removal did not approach the 98% which it was designed to achieve. The decreased efficiency may have resulted from clogging of the GAC with Fe, Mn, bacteria or organics. The GAC units continued to have problems with gamma emissions and adsorbed enough ^{226}Ra to be classified as a low level radioactive waste in the State of New Hampshire. Problems with the aeration systems involved dilution of off-gas plumes, precipitation of Fe and Mn, clogging with bacteria and, in the case of the packed tower, freezing.

The suitability of any of these systems for treating drinking water contaminated with radon is directly related to the influent radon activity. Extrapolation of the data from this study to much lower or higher influent concentrations may not be possible.

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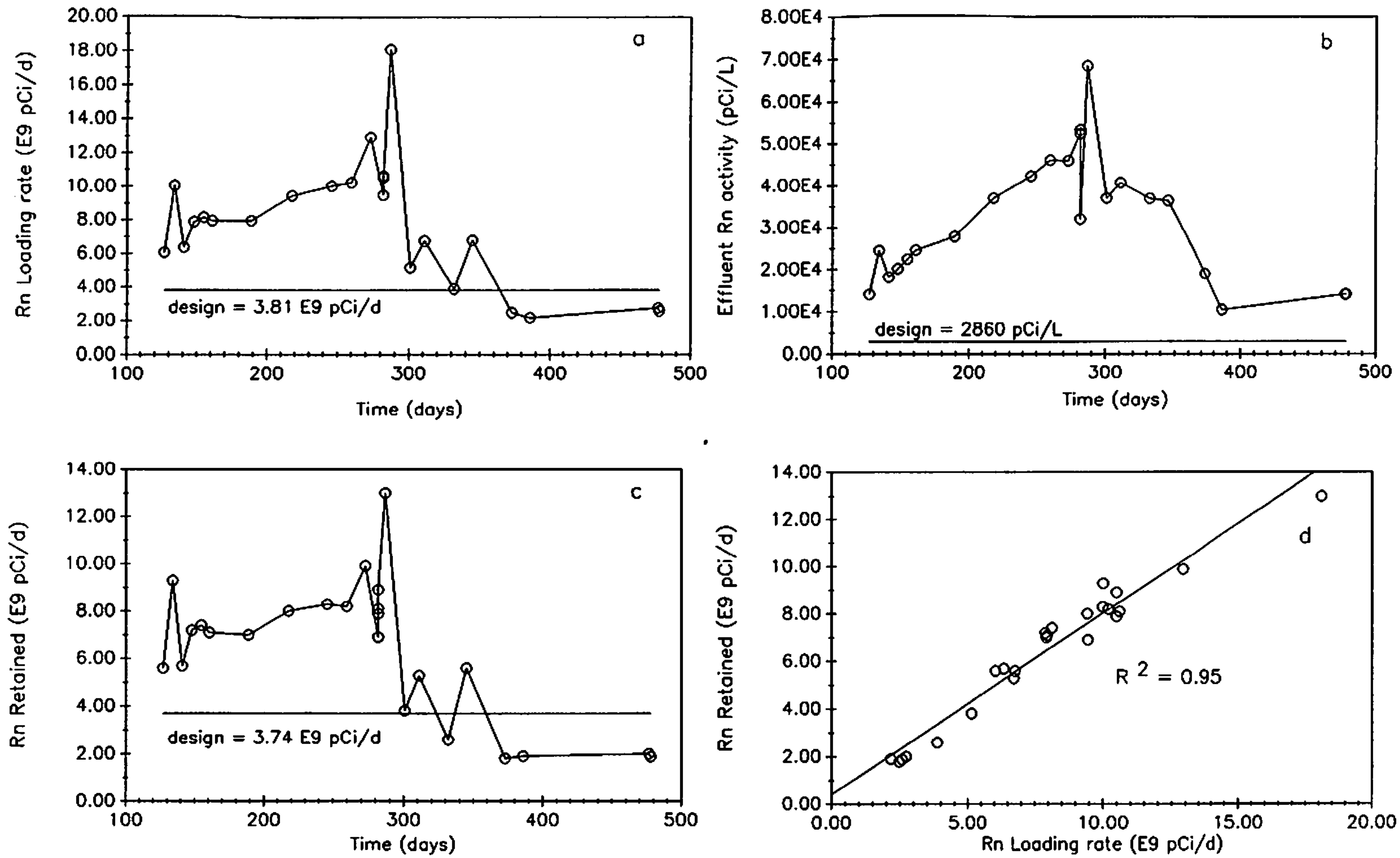

FIGURE 1. GAC Characteristics: a) Rn loading rate b) Effluent Rn activity c) Rn retained d) Rn retained vs Rn loading rate.

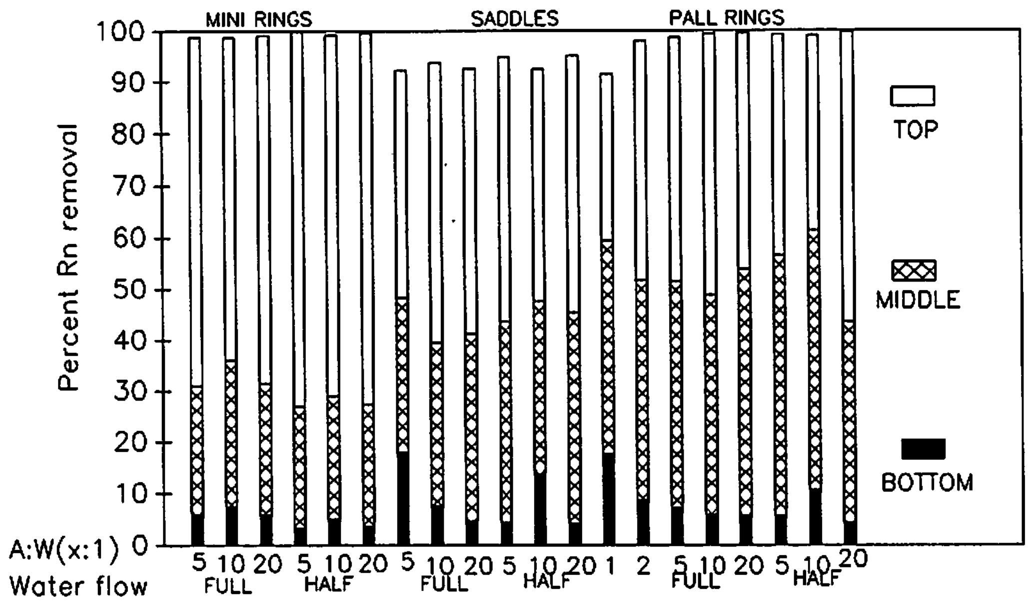

FIGURE 2. Packed Tower Aeration – Percent Rn removal for each packing type, air:water ratio and flow condition.

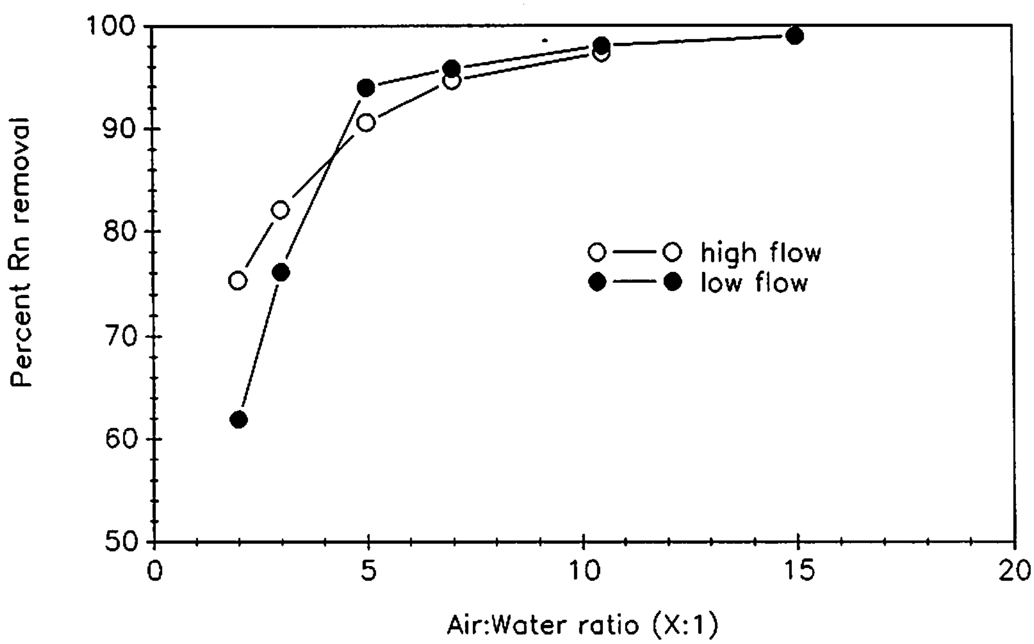

FIGURE 3. Diffused Bubble Aeration – Percent Rn removal high flow (27–33 gpm), low flow (12 gpm).

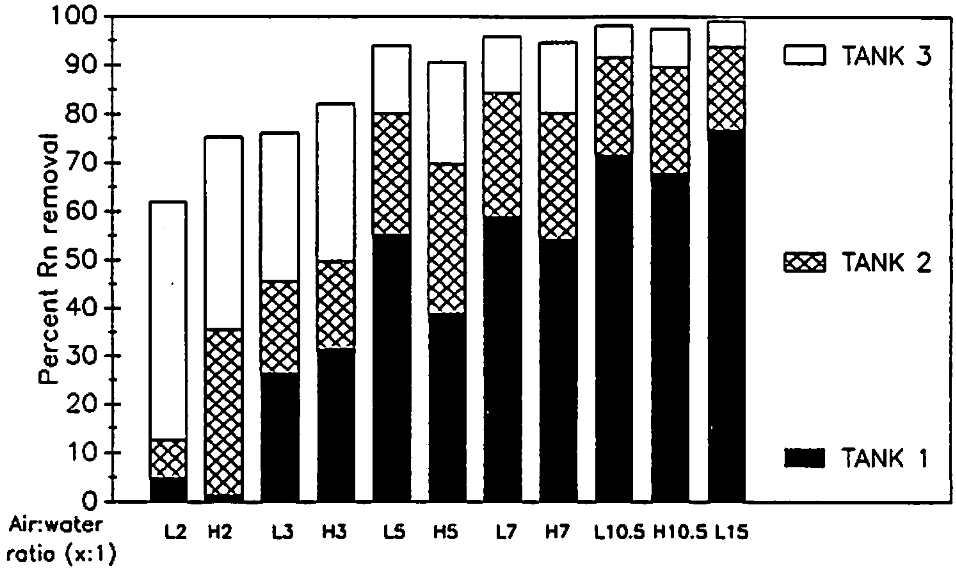

Figure 4. Diffused Bubble Aeration – Percent Rn removal vs Air:water ratio at High (H) and Low(L) water flows for each tank.

TABLE 1. U AND Ra ACTIVITIES ON THE GAC*

Core Sample	^{238}U (Ci/m^3)	^{235}U (Ci/m^3)	^{226}Ra (Ci/m^3)
GAC #1 Top	3.04×10^{-4}	1.07×10^{-5}	1.25×10^{-6}
" Middle	1.89×10^{-4}	6.89×10^{-6}	9.54×10^{-7}
" Bottom	1.75×10^{-4}	6.51×10^{-6}	9.54×10^{-7}
GAC #2 Top	3.77×10^{-5}	1.71×10^{-6}	1.13×10^{-6}
" Middle	7.49×10^{-6}	2.38×10^{-7}	8.30×10^{-7}
" Bottom	7.88×10^{-8}	BDL	8.22×10^{-7}

*De minimus levels according to NH regulations

$^{238}U = 2.5 \times 10^{-5}$ Ci/m^3
$^{235}U = 2.5 \times 10^{-5}$ Ci/m^3
$^{226}Ra = 1.9 \times 10^{-8}$ Ci/m^3

BDL = Below detection limit