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NEW DEVELOPMENTS AND CONSIDERATIONS FOR RADON REMOVAL FROM WATER SUPPLIES

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ABSTRACT

New developments and considerations in the removal of Rn from household and public water supplies have changed the relative effectiveness and applicability of the various treatment alternatives. In point-of-entry (POE) applications, the gamma exposure potential and disposal questions associated with spent GAC beds are considerations that must be taken into account. The new EPA MCL for Rn is expected to be very stringent will likely be the standard used by the mortgage industry in real estate transactions. Typical single-unit GAC installations will not be able to achieve it in many cases.

Diffused bubble aeration has recently emerged as a viable alternative to GAC and packed tower aeration in POE and public water supply Rn removal, respectively. A new multi-staged unit achieves essentially complete removal of Rn from POE supplies. A new modular multi-staged diffused bubble system has been developed for Rn removal from public water supplies. Efficiencies of greater than 99 percent can be achieved for flows up to several hundred gpm.

BACKGROUND

The feasibility of removing radon-222 (Rn) from household and small public water supplies with granular activated carbon (GAC) or aeration has been reported by various researchers (1-21) and a detailed report for public water supplies has recently been prepared for the US Environmental Protection Agency (EPA) (9). This and future research and demonstration will have added significance when the EPA sets a maximum contaminant level (MCL) for Rn in public water supplies. While the new MCL directly applies only to public systems, the MCL for a given contaminant is normally the level that the household mortgage industry uses in mortgage transactions.

The purpose of this paper is to convey some of the latest developments in the point-of-use (POE) and small public water supply applications of Rn removal. It contains the latest information about gamma radiation, shielding requirements, disposal of GAC beds, and the latest aeration results from privately funded research.

GAC ADSORPTION/DECAY

A recent research report (23) entitled "Radon Progeny Accumulation in Field GAC Units" documented the latest results for gamma exposure from the decay of adsorbed lead-214 (Pb-214) and bismuth-214 (Bi-214) and the disposal concerns for accumulated lead-210 (Pb-210), bismuth-210 (Bi-210), and polonium-210 (Po-210). A third aspect of GAC adsorption/decay of Rn is that approximately 5 percent of 125 units monitored routinely are exhibiting unexpected poor performance believed to be caused by water quality-related fouling. Each of these three aspects should be addressed when GAC is considered for Rn removal. The following information will provide guidance in the application of GAC.

GAMMA EXPOSURE RATE

The first GAC unit designed for Rn removal was installed in 1980. Limited work by Lowry and co-workers (6,10,14) and the EPA (24) have documented the elevated steady state gamma exposure rate levels associated with various GAC installations. Recently, Dr. Rydell of the EPA developed a computer model to predict this phenomenon (25).

The most complete documentation of the gamma exposure aspect is by the previously mentioned Rn progeny accumulation study. Ten existing GAC sites were selected to cover a range of Rn levels from 2600 pCi/L to over 1,000,000 pCi/L, to generate a general relationship between gamma exposure and the influent Rn level in POE applications. The gamma exposure field surrounding each GAC unit was accurately defined by up to 400 individual readings with Victoreen, Model 290, survey meters. At three sites, including one of the highest Rn water supplies documented to date, the measurements were repeated with a 0.25 inch lead shield and a 24-inch and 30-inch diameter water shield tank. The water shield tanks contained the GAC vessel and surrounding water.

The raw gamma exposure rate data were consolidated and analyzed with reference to the guidelines for radiation exposure, listed in Table 1. Background varied from site to site and a value of 15 uR/hr was selected. Considering the worst case to be a sleeping individual getting 8 hr/day exposure in the vicinity of a GAC unit, a simplistic relation of acceptable distance vs. Rn level in the raw water was generated from the data. As shown in Table 1, three scenarios were used to indicate relative exposure significance and the acceptable maximum exposure rates, including the background contribution. Using this approach, the acceptable rates ranged from 1727 uR/hr to 73 uR/hr for the most liberal and stringent scenarios, respectively.

TABLE 1. Scenario Definitions Using Guidelines for Radiation Exposure

Scenario	Guideline Exposure mR/yr	Maximum Using an 8-hr/d Exposure, mR/hr	Maximum Exposure Rate with a 15 uR/hr Background, mR/hr
A	Occupational - 5000	1.712	1.727
B	Public - 500	0.171	0.186
C	Residential - 170	0.058	0.073

From National Council on Radiation Protection Report No. 39, 1971.

The Rn levels at the ten sites are summarized in Table 2. The averages represent a three-week sampling period during which 15 raw water grab samples were taken. An example of the resulting gamma exposure rate field surrounding a GAC unit is presented in Figure 1. The designations "A", "B", and "C" reference guideline levels previously presented in Table 1.

TABLE 2. Summary of Radon Sampling Program at Ten Sites

	Radon Levels, pCi/L							Coefficient of Variation, %	
		Well			Treated		Removal,		
Site	Maximum	Average	Minimum	Maximum	Average	Minimum	Percent	Well	Treated
1*	3,080	2,619	1420	535	383	154	85.4	16.4	35.5
2	21,300	16,540	12,600	97	50	33	99.6	14.1	45.7
3	43,600	34,600	24,900	223	148	81	99.6	12.7	31.7
4	90,300	40,780	10,900	30,100	6,860	980	83.2	84.2	155.
5	66,400	53,700	18,900	5,670	4,650	3,440	91.7	30.6	18.5
6†	125,000	95,550	34,300	12,600	7,970	5,880	91.7	34.3	29.9
7	128,000	107,200	74,800	1,310	1,080	830	99.0	13.7	13.2
8	164,000	125,600	21,100	2,190	717	136	99.4	30.4	105.
9	1,080,000	768,800	273,000	5,780	4,730	2,700	99.4	27.7	24.9
10	85,000	63,330	51,400	236	207	180	99.7	16.7	8.96

* - These units contained 3.00 cu ft of Calgon Filtrasorb 400 GAC when installed.
† - These units contained 3.00 cu ft of Barnaby Cheney 299 GAC when installed.
Note: all other units contained 1.70 cu ft of Barnaby Cheney 299 when installed.

The reduced data from the ten sites allowed two important general relationships to be developed. The first is the maximum gamma exposure rate that can be expected for a GAC unit treating a given level of raw water Rn. This level is located at the vessel surface at a height corresponding to the top of the bed if it is operated in the normal downflow mode. The resulting relationship is presented in Figure 2. These data yield a relation of 1.0 mR/hr per 10,360 pCi/L of Rn in the raw water and would apply to GAC units that have reached a steady state operation with respect to Rn removal.

As expected, the wide range of gamma exposure rate measured was a direct function of the raw water Rn levels. This is well illustrated by the data in Figure 2. This is significantly higher than the previously reported level of 1.0 mR/hr for each 17,800 pCi/L of Rn (6). The earlier relation was derived from much less rigorous data, involved a lesser quality gamma/beta survey instrument, and was based upon data from less efficient and larger diameter GAC beds. This last factor could cause a lower value of gamma to be measured; however, at the present time it is suspected that the instrument used was calibrated against a different standard.

The second, and more important, relation that was derived from the gamma surveys is that between acceptable distance and the raw water Rn level. This relation is shown in Figure 3. This figure shows the distance required to

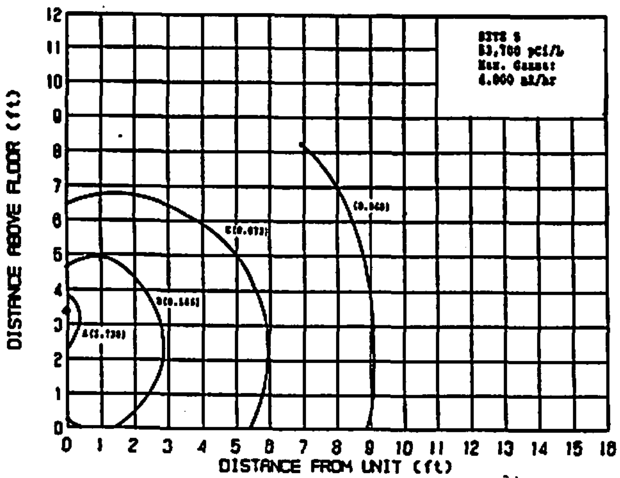

Figure 1. Gamma Exposure Field At Site No. 5: Rn = 53,700 pCi/L

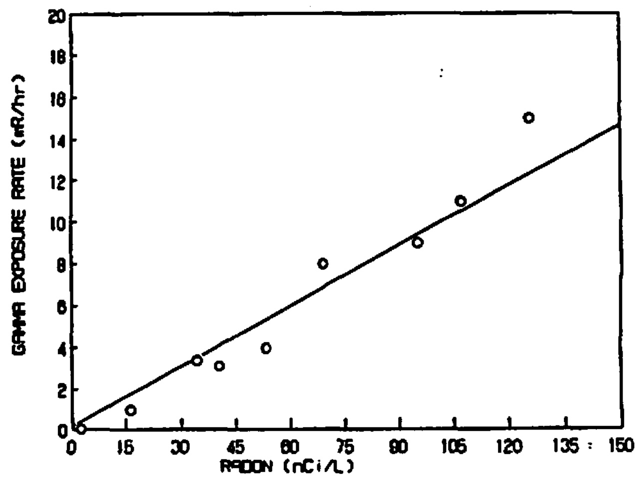

Figure 2. Maximum Gamma vs Rn Level For GAC Units Treating 0 - 150 nCi/L Rn

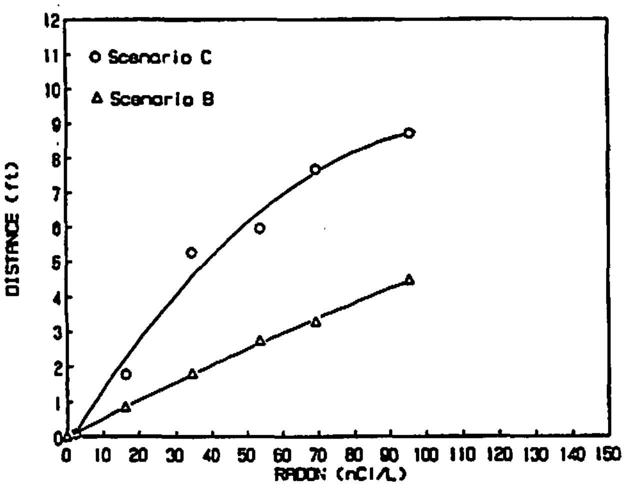

Figure 3. Distance Required to Meet Exposure Guidelines: Rn < 100 nCi/L

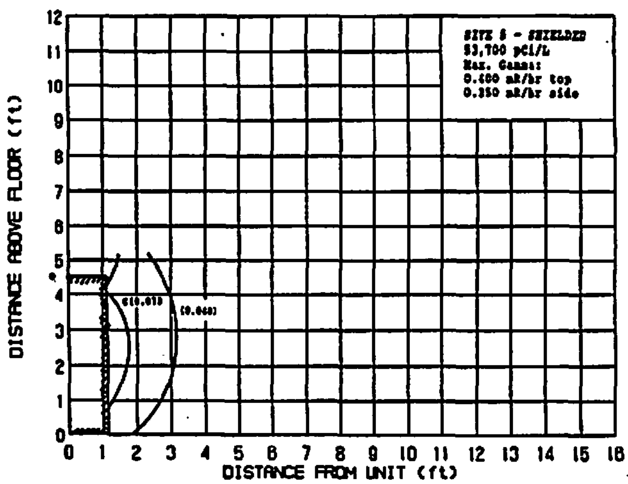

Figure 4. Gamma Exposure Field At Site No. 5 - w/Water Shield

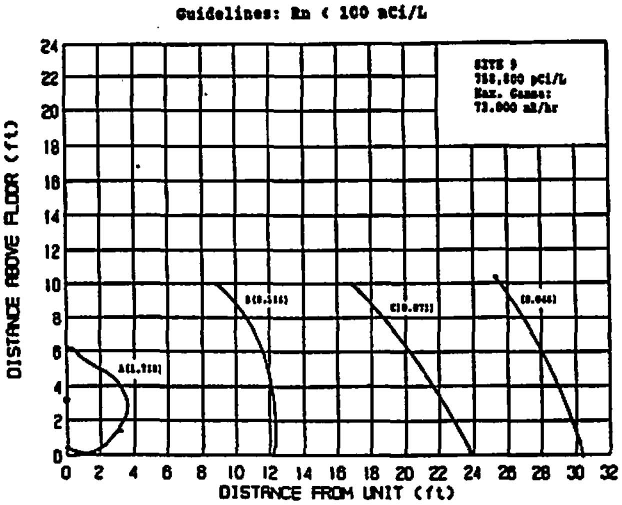

Figure 5. Gamma Exposure Field At Site No. 9: Rn = 758,800 pCi/L

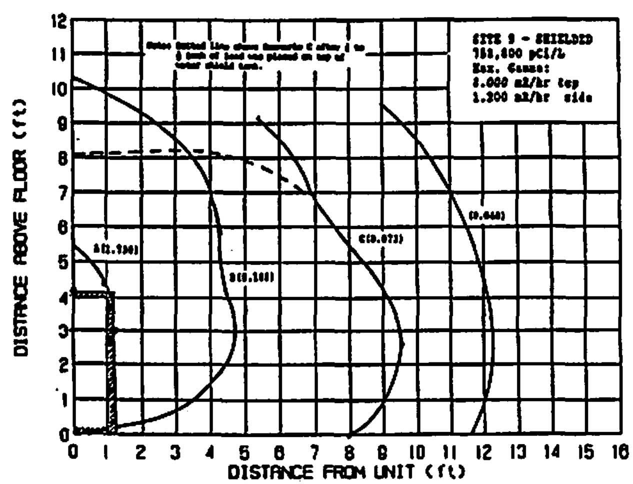

Figure 6. Gamma Exposure Field At Site No. 9 - w/Water Shield

be equal to or less than the exposure guidelines previously explained, assuming an 8-hr exposure per day. A second order polynomial regression line was used to empirically fit the data. The resulting equations for the two scenarios are listed below:

Figure 8: "C" : $D = -0.219 + 0.164*Rn - 0.0007*Rn^2$: Rn = 0 to 100 nCi/L
Figure 8: "B" : $D = -0.002 + 0.054*Rn$: Rn = 0 to 100 nCi/L

where D equals distance from the unit horizontally in feet and Rn equals the radon level in the raw water in nCi/L.

The data presented in Figure 3 can be used to analyze the need for precautions to be applied to specific installations of GAC treatment for Rn. Scenario C shows that if a GAC unit is located downstairs in an area that is not routinely occupied, the need for shielding is slight up to about 100,000 pCi/L. The 100,000 pCi/L Rn level is used because if the downstairs area is not lived in then it is the upstairs living area above the unit that will dictate shielding requirements.

If the location, upstairs or down, where the GAC is installed is a normal living area, and it is assumed, for the sake of discussion, that the Scenario C line should be no more than 3 feet away from the unit, then a GAC unit should be shielded if the raw water Rn is greater than 21,000 pCi/L. The value of 3 feet used here is entirely arbitrary, but illustrates that the need for shielding is totally dependent upon the acceptable distance to the Scenario C guideline.

The actual value that is deemed acceptable is at the present time entirely up to the homeowner. The most strict guideline level has been used in this presentation in an effort to be conservative; however, it may be that informed individuals familiar with radiation will choose to accept a less conservative approach. Several homeowners have indicated that they would do that to save on the installation of a treatment device. They would opt for GAC without shielding to save money, and accept a greater potential for additional gamma radiation exposure somewhere between the Scenario C level (residential) and the Scenario B level (public).

Another case to consider is where a strict limit on the maximum level of gamma exposure rate at the source (GAC vessel) is imposed. For example, a restriction of 2.0 mR/hr as a limit for a GAC unit in the home would require that any supply having greater than 20,000 pCi/L of Rn would need to be shielded.

The above discussion considers only the technical aspects of minimizing the potential for increased gamma exposure over normal background. It is our experience that most homeowners will desire to have absolutely no increase in the potential for gamma exposure over normal background levels. This would mean that, except for the lowest wells containing less than a few thousand pCi/L, GAC treatment is not a viable method of treatment without significant shielding.

SHIELDING GAC UNITS

Three sites in the progeny accumulation study included comparative measurements with and without shielding. Sites 5 and 9 had a simple water shield tank surrounding the GAC tank and Site 10 had a 0.25 inch lead jacket that extended approximately 50 percent down the vessel. The 24 in. diam. water vessel at Site 5 gave a maximum of 13 inches of water shield and the 30 in. diam. vessel at Site 9 gave a maximum of 14 inches of water shield. These values were obtained by locating the GAC vessel against the wall side of the water tank rather than in the center of the water vessel. This is usually possible since the GAC units are normally installed against a below grade wall or in a corner of the basement or cellar.

At Site 5 the shield reduced the horizontal distance required to meet Scenario C from 6.0 ft to 0.7 ft from the side of the shield. It also reduced the maximum gamma exposure rate from an unshielded level of 4.00 mR/hr down to a shielded level of 0.25 mR/hr. The water shield also significantly reduced the gamma exposure rate at distances between horizontal and vertical, as shown in Figure 1 and 4. However, directly above the GAC unit the water shield did not diminish the gamma exposure rate because the water level in the tank only was as high as the top of the GAC unit. A taller water shield and modified plumbing could solve this problem but a small amount of appropriately placed lead directly over the top of the installation can accomplish the necessary shield where required.

Figures 5 and 6 show the gamma field surrounding the GAC at Site 9 for the unshielded and shielded cases, respectively. The effect of the water shield is dramatic, reducing the maximum gamma exposure rate on the side of the vessel from 73.0 mR/hr to 1.20 mR/hr. The horizontal distance required to meet Scenario C was reduced from 24 ft to 9.5 ft. Since the GAC is located in a cellar location that is not routinely occupied, this amount of shielding is considered to be sufficient. The critical area directly upstairs was brought down to an acceptable level by the addition of a small amount of lead sheet placed on the top of the water shield tank. This effect is graphically illustrated by the dotted line for Scenario C in Figure 6. Thus, the most extreme case ever documented for a GAC unit treating Rn was effectively shielded with water. Even so, it is difficult to question the long term need to shield this unit or locate it outside of the household.

The shielding at Site 10 involved a 0.25 inch thick lead jacket extending approximately 50 percent down the side of the GAC vessel. Overall, the lead reduced the maximum gamma exposure rate on the GAC vessel from 8.0 mR/hr to 2.4 mR/hr. The horizontal distance required to meet Scenario C was reduced from 7.7 ft to 4.5 ft. Unfortunately, there was not sufficient room for a water shield in the installation area and, therefore, the lead shield was appropriate.

ACCUMULATION OF PB-210, BI-210, AND PO-210 ON GAC

The recent radon progeny study (23) discussed above provides the latest information on this aspect of GAC use in POE Rn applications. To determine the degree of secular equilibrium attainment for Pb-210 and Po-210, the Rn steady state activity was calculated and then the Bateman equations were used to calculate the fractional attainment (26). The radon activity at steady state was calculated using the following equation:

$$\text{Rn Activity} = 5.5 * Q * (Rn_i - Rn_t),$$

where 5.5 is the mean life of a radon atom (days), Q is the average flow (L/day), and Rn_i and Rn_t are the influent and treated concentrations of radon (uCi/L).

The levels of radon on the GAC at steady state are given in Table 3. The steady state radon activity ranged from a high of 5.45 mCi/L at Site 9 to a low of 4.22 uCi/L at Site 1. It is important to note that the four short-lived progeny of radon are also at the same activity as radon, making the total steady state activity on the GAC equal to a minimum of five times the radon activity plus the accumulated Pb-210, Bi-210, and Po-210.

If it is assumed that Rn and its first four short-lived progeny are in secular equilibrium on the GAC bed, it is relatively simple to apply the Bateman equations to calculate the fractional degree of secular equilibrium for the final four progeny, including stable Pb-206, over any period of time. This model was applied to each of the sites, taking into account the amount of water usage, the Rn level in the raw water, and the time the unit had been in operation. The resulting values for the three longer lived isotopes were presented in Table 3.

TABLE 3. Site Characteristics of Rn Progeny Study

Site	Location	Radon Levels, pCi/L Well	Treated	Water Use, L/day	Time in Service, mo	Radon Activity,* microCuries	Percent of Secular Equilibrium Pb-210	Po-210	Maximum Activity, microCuries Pb-210	Po-210
1	Gorham, ME	3,619	303	343	36	4.22	0.66	0.65	0.36	0.31
2	Belgrade, ME	16,560	59	333	30	29.8	5.08	3.37	1.51	0.98
3	Manchester, ME	34,600	168	443	9	76.6	2.31	0.82	1.76	0.63
4	Mech. Falls, ME	40,700	6,159	342	43	67.6	10.6	8.81	7.15	5.55
5	Vassalboro, ME	53,700	4,451	269	16	96.6	4.07	2.31	3.30	1.31
6	Auburn, ME	55,550	7,970	939	72	453.	17.1	15.5	77.3	70.0
7	Boothbay, ME	107,260	1,055	532	21	311.	3.03	1.32	8.79	3.79
8	Freeport, ME	125,600	717	553	7	380.	1.79	0.45	6.80	1.71
9	Leeds, ME	758,000 1,126,000†	4,739	616‡	22	5,450.	5.55	3.74	303.	204.
10	Casco, ME	69,320	208	431	8	159.	3.07	0.66	3.39	1.02

* Steady State Rn Activity = (5.50)(Flow, L/d)(Rn Removed, uCi/L)

† 758,000 pCi/L was the average for three week monitoring period; 1,126,000 pCi/L was the average for the first 400 days of service; 1,126,000 was used for the long-lived progeny calculations.

‡ Water use for the three week period was 355 L/d; water use for the first 400 days of service was 877 L/d; the average of these two values was used.

The range of secular equilibrium achievement was 1.79 to 17.09 percent for Pb-210. The range of Pb-210 activity accumulation was calculated to be 0.36 to 303 uCi. The Bi-210 activity can be assumed to be equal to the Pb-210 activity, since the ratio of half-lives, Pb/Bi, is high. The Po-210 activity approaches the Pb-210 activity as the period of operation increases. For the Sites with higher Rn, Table 3 indicates that the levels of adsorbed Pb-210, Bi-210, and Po-210 are significant.

For Site 9, the total accumulated activity on the GAC is equal to 28.1 mCi, comprised of 5.45 mCi radon, 5.45 mCi each of Po-218, Pb-214, Bi-214, and Po-214, 0.30 mCi each of Pb-210 and Bi-210, and 0.20 mCi of Po-210. This is a relatively high amount of radioactivity compared to other natural sources and illustrates the degree to which radon and its progeny can accumulate on GAC.

While all data thus far indicate that the progeny of radon remain securely adsorbed to the GAC surface, this area requires further investigation and documentation as very little data on this subject has been collected.

The GAC unit at Site 9 was purchased from the homeowner, by Lowry Engineering, to be included in the measurements for Pb-210. It was allowed to decay for over two months and then accurately quantified in-situ with a germanium detector. The distribution of Pb-210 was determined using a portable Canberra reverse electrode co-axial germanium detector system from the University of Maine Department of Civil Engineering Radon Research Laboratory.

The data from the in-situ Pb-210 quantification of the Site 9 GAC bed is shown in Figure 7. The measured values of Pb-210 at the indicated depths in the bed allowed the total quantity in the bed to be determined by direct integration. The predicted value, based upon water use, operating time, and the radon level in the well over the entire period of operation, gave a total Pb-210 value within 2.0 percent of the measured value. It is suspected that while the technique used is very good, there really is more variation than this to be expected arising from the reliability of the raw water average radon and, to a lesser extent, the metering of water use. Overall the data are excellent and indicate a total retainment of Pb-210.

DISPOSAL OF SPENT GAC

At the present time all data indicate that the accumulation of Rn progeny on GAC does not pose a health problem to the homeowner, assuming adequate shielding of the gamma exposure rate in certain cases. It is expected that the progeny of Rn are tightly held in the smallest micropores of the carbon since that is where they are produced by Rn decay. It is assumed that they are retained by forces stronger than physical adsorption within these very small micropores and since the progeny of Rn are all very reactive chemically at surfaces, this is probably a valid assumption. Thus, the question concerning these progeny on the GAC is one of ultimate disposal of the GAC, which may be a difficult one for many states to answer.

The Atomic Energy Act of 1954, as amended, authorizes the U.S. Nuclear Regulatory Commission (NRC) to regulate source, byproduct, and special nuclear material. However, not all sources of radiation are regulated by the NRC. Naturally occurring radioactive material, generally referred to as NARM, and most accelerator produced material and x-ray devices are almost entirely excluded from federal regulatory control.

All naturally occurring radioactive substances, including U, Ra, Rn, and their progeny, are not subject to the Code of Federal Regulations (10 CFR) enforced by the NRC. Individual states, however, are not prohibited from regulating NARM. The alternatives for handling the potential problem of radioactive GAC from Rn removal applications are as follow:

1. Redefine the Exempt Quantity. Table A of 10 CFR part 35 lists the exempt quantities for licensing. Pb-210 has an exempt quantity of 0.1 uCi. This means that less than 0.1 uCi of Pb-210 can be disposed of as ordinary

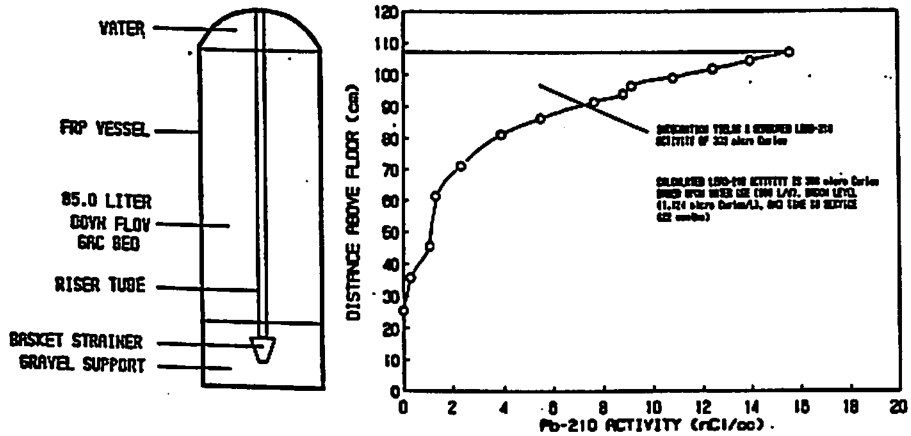

Figure 7. Measured and Calculated Pb-210 Activity on GAC Bed From Site 9 After 22 Months of Operation

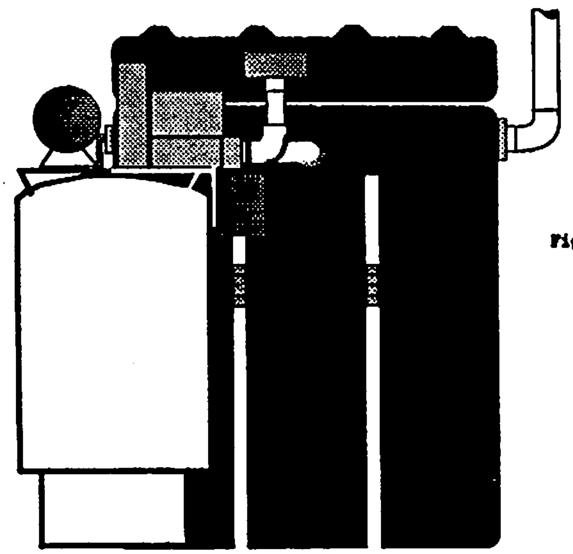

Figure 8. Drawing of the Stripper Multi-Staged Aeration System

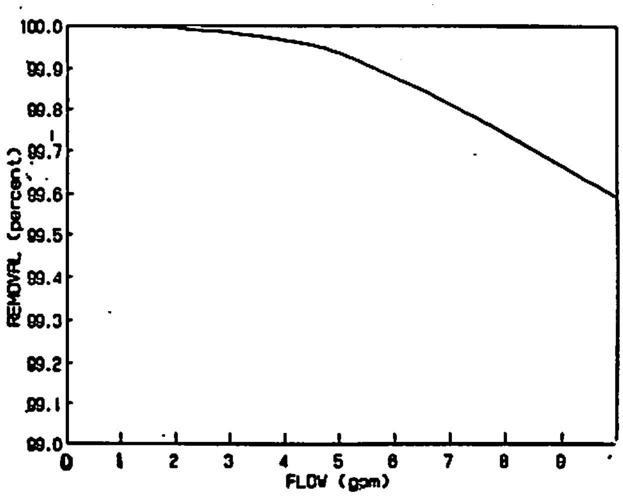

Figure 9. Steady State Performance of the POE Stripper Multi-Staged Aeration System For Rn Removal

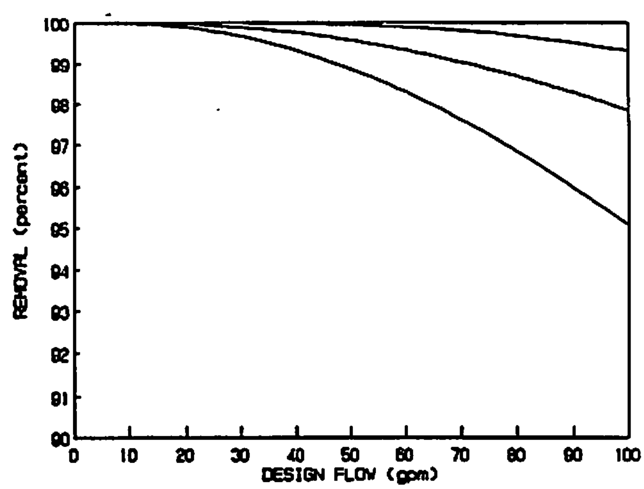

Figure 10. Performance Curves For Three Models of the Stripper for Public Water Supply Application

refuse without regard to its radioactivity. Considering the adsorption/decay of Rn and its progeny on a GAC bed, the accumulation of Pb-210 will exceed 0.1 uCi within 9 months for a household using 1000 L/d of water containing only 1000 pCi/L of Rn. An alternative might be to raise the exempt quantity for Pb-210 and its progeny. However, with an increase of 10X nine of the ten GAC units shown in Table 3 would exceed the new exempt quantity of 1.0 uCi. It must be reemphasized that most of the GAC units shown in Table 3 are treating exceptionally high Rn wells and that the majority of future GAC beds will be treating supplies with lower Rn levels and, therefore, will have much less Pb-210 accumulation. Nevertheless, an exempt quantity of 1.0 uCi would not eliminate the problem because most GAC beds will remain effective and in service for a number of years.

2. **Dispose of GAC Beds at Pre-Set Intervals.** This alternative would require all water treatment specialists to be registered or licensed. Each GAC device sold would be on record with the water treatment specialist and/or the state. Using the theoretical accumulation of Pb-210 on GAC, it would be relatively simple to determine when the GAC bed would reach the exempt quantity accumulation. Prior to that time, the installer, or the state, would notify the home owner that the carbon would have to be replaced.

3. **Formal Licensing of GAC Units.** This alternative would eliminate the problem but would create many others associated with the regulatory process. This should be considered as a last resort, and as an adjunct to alternative No. 2.

4. **Prohibit GAC Units.** The prohibition of all GAC Rn removal units, which includes virtually all that treat ground water, would necessitate the call for a replacement treatment method. Currently, the only alternative to GAC is aeration. Aeration avoids the radiation and disposal problems associated with GAC and can be very efficient. This alternative would create many problems as GAC is a valuable and popular water treatment media currently in widespread use.

5. **Ignore the Problem.** This is an easy choice for the states and the alternative that has been selected during the first several years since the problem has been identified and documented. Several states are currently studying the problem and the alternatives for dealing with it. It is hoped that the problem will be addressed, rather than ignored.

PREMATURE FOULING OF GAC

During the last two years, field data from the routine monitoring of nearly 100 GAC units has indicated a problem with premature deterioration of the effectiveness of approximately one out of 20 units. Further, the problem appears to be largely confined to a specific region, namely northwestern New Jersey. It is presently suspected that the problem is related to the particular natural water quality, rather than to a specific type or batch of GAC product. Speculation about the possibility of iron chemistry being important has not led to any concrete conclusions and at the present time there is no explanation for this occurrence. In other regions there are no reported or documented instances of the fouling problem, and in the specific New Jersey region we estimate that the potential for failure is relatively high.

AERATION

Aeration can be very effective for the removal of Rn from POE water supplies, and has certain application for small and large public water systems. In the POE application, effective and economical aeration systems have generally not been available and, therefore, have had limited use. Previous aeration systems designed specifically for Rn removal have been reported to be relatively costly, at between $3000 and $4000, and only remove 85 to 95 percent of the Rn in the raw water supply (2,16). These systems use spray aeration or packed tower aeration technology, which are limited to lower removals in POE application. Without the capability of greater than 95 percent removal, a Rn removal system will be limited to wells containing less than 4000 pCi/L, assuming a 200 pCi/L MCL. In contrast, diffused bubble aeration is unlimited in its removal efficiency in POE application and has been shown to be capable of complete Rn removal (14,20,21).

A multi-staged diffused bubble POE aeration system has been developed for Rn removal during the past year and 22 prototype systems have been installed and monitored in seven states (20,21). This system is patented and was first applied to petroleum contamination problems in POE treatment (27). The performance of single and two-stage prototype systems for Rn removal has ranged from 92 percent to 99.9 percent. These systems treat levels of Rn from less than 20,000 pCi/L to over 500,000 pCi/L. This research led to the development of a commercial unit soon to be marketed for POE Rn removal.

The commercial version of the multi-staged diffused bubble aeration system is trade marked "the Stripper" and it became available in September 1988. A drawing of the system is shown in Figure 8. The space requirement for the system is 44 in(L) X 34 in(W) X 44 in(H). The performance of the Stripper is shown in Figure 9, where the removal is shown as a function of constant steady flow. Removals from 99.5+ percent to 100 percent are achieved over a 0 - 10 gpm range of flow. In the actual POE application, research has shown removals approaching 100 percent. In summary, the degree of Rn removal will not be an issue with the new aeration system and any POE water supply will be taken to below the most stringent MCL level envisioned.

AERATION FOR SMALL PUBLIC SUPPLIES

While the small POE system is capable of excellent treatment in very small public water supply applications, a larger modular vessel has been developed to treat flows in the 100 to 400 gpm flow range. The larger system will compete favorably with packed tower aeration, being capable of greater removal efficiencies for less capital expenditure - an important consideration for these small public supplies. Other advantages of the multi-staged diffused bubble system include its low profile (less than five feet) compared to a packed tower system. The performance curves for three of the public water supply models are shown in Figure 10.

ECONOMICS

Past research reports and experience with Rn removal have documented GAC as being more cost effective than aeration for POE application. The new stringent EPA MCL will change this because GAC systems must be made larger for wells containing greater than 5,000 to 10,000 pCi/L. For example, while most GAC units achieve removals greater than 99 percent, a significant fraction achieve removals between 95 and 99 percent. In short, our experience indicates that it is difficult to guarantee 99 percent removal with a 1.75 to 2.5 cu ft bed of GAC in all cases. This means that for a stringent MCL goal and a well that contains over 5,000 to 10,000 pCi/L of Rn, two GAC units in series may be required. In addition, wells that contain this level of Rn should be shielded, for reasons of good will and peace of mind for the household occupants. The resulting GAC system for wells over 5,000 to 10,000 pCi/L would cost approximately $2100, installed.

For wells containing less than 5,000 pCi/L of Rn, a treatment system should be capable of achieving a minimum removal of 96 percent. The cost of a single GAC unit system would be approximately $1000, installed.

The installed cost of a Stripper is approximately $2300 - $2500, making it essentially equal to GAC for wells with Rn levels above 5,000 to 10,000 pCi/L. For wells below 5,000 pCi/L GAC is clearly more cost effective, if disposal does become an issue. Since gamma exposure should not be an issue for these lower Rn wells, GAC appears to be the best alternative. This conclusion carries with it the assumption that the GAC is not subject to the premature fouling problem previously discussed. It should be re-emphasized that if in the future, spent GAC must be disposed of in a low-level radiation facitly, then the use of GAC for POE Rn removal will become prohibitively expensive.

For public water supplies, aeration is more cost-effective than GAC due to the relatively high GAC empty bed contact time necessary for high removals. Both diffused bubble and packed tower aeration have been applied in the field (1,7). A new multi-staged diffused bubble aeration system designed for Rn removal appears to offer distinct advantages over packed tower aeration for small supplies up to approximately 400 gpm.

CONCLUSIONS

1. The maximum gamma exposure rate on a GAC vessel is a nearly a direct function of the level of Rn in the water. An empirical relationship of 1.0 mR/hr per 10,360 pCi/L of Rn was found for ten sites.

2. The levels of gamma exposure at distance from the GAC vessel is largely a function of the level of Rn in the raw water.

3. If the occupants of the home insist on no increase in their gamma exposure due to a GAC unit treating Rn, then GAC is not a good alternative. Exceptions would be when the Rn level in the raw water is less than 5,000 pCi/L and when an adequate shield is used.

4. Shielding with a water vessel is very effective and the data indicate that virtually any household application of GAC can be effectively shielded if the unit is located in a non-living area.

5. A GAC bed treating approximately 1.1 X 10^6 pCi/L Rn for 22 months accumulated a measured quantity of Pb-210 of over 300 uCi. Pb-210 appears to be completely retained.

6. The measured levels of accumulated Pb-210 and the calculated levels of accumulated Po-210 are very significant in GAC beds treating high concentrations of Rn. Using stringent exempt quantities as a guide for determining the classification of low level radioactive waste, it can be shown that the majority of GAC units treating groundwater with even low Rn levels will fall in that category.

7. It appears that a life of 10 years is not going to be uncommon for a GAC bed treating Rn. Therefore, if stringent limits are enforced on the accumulation of long-lived progeny they will be the controlling factor on how long a GAC bed should remain in service.

8. Approximately 5.0 percent of the total units monitored routinely by Lowry Engineering have exhibited premature failure, as defined by a gradual decrease in the removal efficiency. Most of these units are confined to a region in New Jersey.

9. A multi-staged diffused bubble aeration system for POE and small public water supply application is available for Rn removal. Removals of greater than 99.9 percent are possible. For wells containing more than 5000 pCi/L of Rn, the POE version compares favorably in cost to GAC treatment.

10. A public water supply version of the new multi-staged aeration system is capable of extremely high removals for flows up to 400 or more gpm.

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