

**RADON REMOVAL USING POINT-OF-ENTRY  
WATER TREATMENT TECHNIQUES**

by

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## FOREWORD

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The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report presents the results of an evaluation, performed by the University of New Hampshire - Environmental Research Group (ERG), of radon removal by 3 point-of-entry water treatment techniques: granular activated carbon, diffused bubble aeration and bubble plate aeration. This research is a follow-up to a larger study of radon removal techniques for small community water supplies. The report discusses each of the treatment alternatives with respect to their radon removal efficiency, potential problems (i.e., waste disposal, radiation exposure and intermedia pollution), and economics in point-of-entry applications.

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## ABSTRACT

Radon is one of the naturally-occurring radionuclides which will be regulated as part of the Safe Drinking Water Act Amendments of 1986. Several studies on the distribution of radon in ground water supplies have indicated that there will be a large number of small public water supplies impacted if a Maximum Contaminant Level (MCL) is set for radon in the proposed range of 200-2,000 pCi/L. Although the regulations do not apply to private water supplies (i.e., individual wells), states normally adopt the Federal regulations and apply them to individual well water supply systems. These private supplies will require point-of-entry (POE) treatment. The purpose of this EPA Cooperative Agreement was to evaluate the performance of POE granular activated carbon (GAC), and diffused bubble and bubble plate aeration systems treating a ground water supply containing radon ( $35,620 \pm 6,727$  pCi/L). The pattern of loading to the units was designed to simulate daily demand in a household. Each of the systems was evaluated with respect to three primary factors: radon removal efficiency, potential problems, and economics.

The radon removal efficiency of the POE GAC units gradually deteriorated over time from 99.7% to 79% for the GAC without pretreatment and from 99.7% to 85% for the unit preceded by ion exchange. It appeared that iron precipitation in the GAC without ion exchange pretreatment impeded radon sorption by fouling the GAC surface or causing channeling of water through the bed. The gamma emissions data indicated that the zone of radon removal slowly moved down the GAC bed. However, in POE applications where the water has low to moderate activity, excess GAC can be supplied with little extra cost, so that the unit may be able to sustain >70% removal of radon for long periods of time, even with variations in radon loading. At higher radon loadings, the GAC units may not be able to dampen variations in influent activity and flow without some increase in effluent activity.

Most GAC systems will require either pretreatment and/or backwashing to prevent fouling resulting from accumulation of particulates, metal precipitates, bacteria or organic matter. If frequent backwashing can control this problem, ion exchange should be avoided because its resin, backwash water and regenerant brine become contaminated with long-lived radionuclides and may require special handling and disposal.

GAC POE treatment systems were found to accumulate long-lived radionuclides, particularly lead-210, which may significantly increase handling and disposal costs. In addition, GAC units receiving high radon loadings will produce gamma emissions that exceed recommended health standards even when water jacket shields are provided.

The bubble plate and diffused bubble POE units were very efficient (>99%) at removing radon from the water. They should be able to meet an MCL in the

range 200-2,000 pCi/L in most cases, even with significant variation in radon mass loading. This resilience is primarily due to the high air to water ratios supplied by the aeration blowers. One major problem associated with the aeration techniques is iron oxidation/precipitation. Iron treatment will be required in almost all POE applications which use aeration. The aeration units are also prone to operational problems because they rely on blowers and pumps to function properly. As a result, they require frequent maintenance. In addition, the off-gas stack should be vented above the roofline to prevent any radon from re-entering the home.

The total production costs for the GAC units were \$9.88/1,000 gallons without pretreatment and \$13.40/1,000 gallons with pretreatment including disposal costs (assuming the GAC and ion exchange resin are low level radioactive wastes). The total production costs for the aeration systems were \$22.58/1,000 gallons (diffused bubble) and \$26.74/1,000 gallons (bubble plate). The aeration costs do not include auxiliary blowers for venting, or air treatment. The production costs for the POE radon removal systems are high relative to public water supplies because (i) there is no economy of scale, and (ii) it is assumed individual homeowners will be purchasing single POE units unlike utilities which could purchase large quantities of POE units for a service area. Therefore, there will not be a quantity discount on the POE equipment for the individual well water supplies.

At low influent radon activities ( $\leq 5,000$  pCi/L), GAC systems are the preferred treatment technique in POE applications where there are not excessive concentrations of long-lived radionuclides in the water. GAC is recommended because it (i) requires the least owner maintenance, (ii) is the easiest system to operate, and (iii) is the least expensive with respect to capital and operation and maintenance costs, even considering disposal costs. At low mass loadings, achieving a high percent removal efficiency is less critical, and the GAC can therefore meet an MCL in the range 200-2,000 pCi/L. In addition, at these loadings gamma emissions are minimized. At higher mass loading rates, aeration techniques would be required to meet an MCL of 200-2,000 pCi/L.

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## SECTION 1

### INTRODUCTION

As part of the 1986 amendments to the Safe Drinking Water Act, the United States Environmental Protection Agency (EPA) will propose a rule for Maximum Contaminant Level Goals (MCLGs) and National Primary Drinking Water Regulations (NPDWR) including Maximum Contaminant Levels (MCLs) for radionuclides in drinking water (Federal Register, 1986). One of the radionuclides that will be regulated under the proposed rule is radon-222\* (hereafter referenced as radon in the text). In a recent status report, EPA (1989a) indicated that it is considering setting the MCL for radon in the range 200 to 2,000 pCi/L. There have been several studies of the distribution of radon in ground water supplies in the U.S. (Hess et al., 1985; Longtin, 1988; Dixon and Lee, 1988; Vitz, 1988), all of which indicate that there will be a large number of private wells and small ( $<76 \text{ m}^3/\text{day}$ ) public water supplies impacted by an MCL in that range.

The rule will also contain recommendations with respect to Best Available Technologies (BATs) and analytical methods. As a result, EPA established a Cooperative Agreement to evaluate the performance of full-scale systems treating small community ground water supplies containing radon (Kinner et al., 1990). Though the rule will not directly affect POE water supplies, EPA also wanted to obtain data on several small-scale radon removal systems, so that information could be available with respect to Best Available Technologies (BATs) for those applications. Granular activated carbon (GAC) adsorption and aeration are the primary processes that have been used to remove radon from drinking water. The GAC process relies on radon's ability to adsorb to the carbon. One unique aspect of GAC treatment is that the breakthrough/exhaustion profile typically seen when GAC is treating conservative contaminants has not been observed during radon removal. GAC units have been used to remove radon from drinking water in several POE applications (Lowry and Brandow, 1985; Lowry et al., 1987; Lowry and Lowry, 1987).

The aeration methods are predicated on the fact that radon is a highly volatile gas with a relatively high Henry's constant ( $2.80 \text{ atm} \cdot \text{m}^3 \text{ H}_2\text{O}/\text{m}^3 \text{ air}$  at  $10^\circ\text{C}$ ) and therefore can be easily transferred from water to air. Both diffused bubble and bubble plate aeration have been used in POE applications (Lowry et al., 1987; LaMarre, 1988 and 1989). Packed tower aeration is rarely used in these conditions because the height of the tower is too great for installation in most homes.

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\*Though there are many radioactive isotopes of radon, radon-222 is the most common.

## RESEARCH OBJECTIVES

The purpose of this EPA Cooperative Agreement was to evaluate the performance of POE GAC, and diffused bubble and bubble plate aeration systems while treating a ground water supply containing radon. In this study, direct comparison could be made among the individual POE systems because they were operated in a parallel flow configuration and were each receiving the same influent water. The raw water came from an abandoned small community ground water supply and contained 22,837 to 54,765 pCi/L of radon. Each treatment system treated  $1.02 \text{ m}^3/\text{day}$  of water applied in six 18 min intervals and one 30 min interval distributed throughout the day. The pattern of application was designed to simulate daily demand for a POE system (Anderson and Watson, 1967). Each of these systems (GAC, diffused bubble aeration, bubble plate aeration) was evaluated with respect to three primary factors: radon removal efficiency, potential problems (i.e., waste disposal, radiation exposure, equipment malfunctions, intermedia pollution) and economics. The study was not intended to develop design equations for these systems, but rather to evaluate their performance over one year of constant operation.

The specific objectives of the study were to:

- Evaluate POE GAC systems, operating with and without ion exchange pretreatment, monitoring them for changes in radon removal, radiation emissions, general water quality parameters (e.g., pH, alkalinity, iron, manganese, turbidity, microbial numbers, and non-purgeable dissolved organic carbon (NPDOC));
- Conduct several special monitoring events of the GAC systems to assess the impact of diurnal variations in water flowrate and raw water quality (i.e., loading rate), and backwashing on GAC performance;
- Core the GAC and ion exchange units after one year of operation to determine if iron, manganese, microorganisms, and/or radionuclides were accumulating in the units;
- Evaluate POE diffused bubble and bubble plate aeration systems monitoring them for radon removal, general water quality parameters and off-gas emissions of radon.

The report is divided into four sections including introduction (Section 1), conclusions and recommendations (Section 2), methods and materials (Section 3), and results and discussion (Section 4). Section 4 includes a discussion of (i) the radon removal efficiency of the systems, (ii) baseline data on other water quality parameters, (iii) potential problems with their operation, (iv) suggestions for design modifications, and operation and maintenance requirements, and (v) an economic analysis of each system. Data from each of the units is discussed and compared in each subsection, where appropriate. Recommendations were made regarding the use of each system in POE applications.

## FUNDAMENTALS OF RADIONUCLIDES

Radionuclides are different from the majority of drinking water contaminants regulated by EPA because of the instability of their nucleus and their ability to decay. This often leads to confusion resulting from the dissimilarity between the units used to describe radioactivity and those used for other water contaminants; as well as the physical meaning of these units. Therefore, a brief synopsis of some of the fundamental principles of radionuclides important to this project is given below.

Radon-222 is part of the uranium ( $4n+2$ ) decay series (Table 1) which originates with uranium-238. Radon and its four short-lived progeny (polonium-218; lead-214, bismuth-214 and polonium-214) have some of the shortest half-lives (less than 27 min) of any of the radionuclides in the series. Radon is the only gas in the decay series and is a member of the Periodic Chart Group 0 (noble) gases including helium, argon and other chemically inert monatomic gases. Radionuclides are described in units of activity (Curies) which indicate the rate at which a radioactive atom is undergoing decay (i.e., nuclear disintegrations). By convention, one picocurie (pCi) means that 2.22 atoms of that radionuclide are decaying per min (disintegrations per min  $\equiv$  dpm). A radionuclide's half-life ( $t_{1/2}$ ) is the time interval during which 1/2 of the atoms decay ( $t_{1/2} = \ln 2/\lambda$  where  $\lambda$  = decay constant,  $0.0075 \text{ hr}^{-1}$  for radon). For radon and its progeny, the half-lives are very short varying from 3.82 days (radon-222) to 0.00016 sec (polonium-214). The actual life of an individual atom, however, can range from 0 to infinity (i.e., decay occurs randomly).

Though the units specified for radionuclides in water are in pCi/L (i.e., activity per unit volume) and their range in ground water is  $10^0$ - $10^6$  pCi/L, the mass and number of atoms present is usually extremely small and can be determined using the equation:  $A = N\lambda$  where  $A$  = activity (pCi or dpm) and  $N$  = number of atoms. For example, 1,000 pCi of radon (2,220 dpm) in a liter of water is only  $1.76 \times 10^7$  atoms of radon or a mass of  $6.49 \times 10^{-15}$  g (radon  $\equiv$  222g/mole) or 6,490 pg/L of water.

Therefore, when designing treatment systems to remove radon from water, though the activities may be substantial (and have important public health significance), the numbers of atoms and mass to be removed is very small. It should also be noted that the mass concentration of radon in ground water (ex., 1,000 pCi/L  $\equiv$   $6.49 \times 10^{-15}$  g/L) is much greater than its concentration in air ( $0.1 \text{ pCi/L} \equiv 6.49 \times 10^{-19}$  g/L).

Detection capabilities for most drinking water contaminants are in the  $10^{-8}$  to  $10^{-3}$  g/L range. The instrumentation used in radon analysis detects light flashes created when the radioactive particles emitted during decay strike fluorescing compounds and therefore, is able to measure lower concentrations ( $32.5 \times 10^{-16}$  g/L = <500 pCi/L). The instrument's detector records the number of counts (scintillations) per minute or cpm. The



TABLE 1. ABBREVIATED\* URANIUM ( $4n + 2$ ) DECAY SERIES

Chemical Notation	Historical Name	Half-life	Radiation Emitted Upon Decay <sup>+</sup>
238 92 U ↓	Uranium	$4.5 \times 10^9$ yrs.	$\alpha$
234 90 Th ↓	Thorium	24.1 days	$\beta, \gamma$
234 91 Pa ↓	Protactinium	1.17 min	$\beta, \gamma$
234 92 U ↓	Uranium	$2.47 \times 10^5$ yrs.	$\alpha, \gamma$
230 90 Th ↓	Thorium	$8.0 \times 10^4$ yrs.	$\alpha, \gamma$
226 88 Ra ↓	Radium	1602 yrs.	$\alpha, \gamma$
222 86 Rn ↓	Radon	3.82 days	$\alpha$
218 84 Po ↓	Polonium	3.05 min	$\alpha$
214 82 Pb ↓	Lead	26.8 min	$\beta, \gamma$
214 83 Bi ↓	Bismuth	19.7 min	$\beta, \gamma$
214 84 Po ↓	Polonium	164 $\mu$ sec	$\alpha$
210 82 Pb ↓	Lead	21 yrs.	$\beta, \gamma$
210 83 Bi ↓	Bismuth	5.01 days	$\beta$
210 84 Po ↓	Polonium	138.4 days	$\alpha$
206 82 Pb	Lead	-	Stable -

\* Protactinium-234 (Uranium Z), Astatine-218, Thallium-210 and 206 are not shown. These represent radionuclides created in <0.2% of the decays of Protactinium-234 (Uranium Xg), Polonium-218, Bismuth-214 and Bismuth-210, respectively.

+ Only listed if % emission is >0.1%.

efficiency of the instrument is usually not 100%, so an efficiency factor must be determined using standards to relate the cpm obtained to the dpm or pCi actually present.

Atoms of the various radionuclides in a decay series are constantly being produced and are, in turn, decaying to form other unstable nuclides. For example, radon is created by the decay of radium-226 ( $t_{1/2} = 1602$  yr) and decays to polonium-218 (radon  $t_{1/2} = 3.82$  days). Because of this continuing pattern of formation and decay, it is important to understand the concept of secular equilibrium. When a radionuclide is in secular equilibrium with another radionuclide or its progeny, there is a constant amount of that radionuclide present which is a function of the rate at which it is being created and the rate of its decay. The mathematical relationships are best explained by Evans (1969). Hence, at secular equilibrium between radon and its progeny or between radium and radon, the activities of the parent and its progeny are equal. For example, when 1,000 pCi/L of radium is in secular equilibrium with radon, the activity of radon will also be 1,000 pCi/L.

## SECTION 2

### CONCLUSIONS AND RECOMMENDATIONS

#### GRANULAR ACTIVATED CARBON

1. The radon removal efficiency of the POE GAC units gradually deteriorated over time from 99.7% to 79% for the unit without pretreatment and from 99.7% to 85% for the unit with ion exchange pretreatment. The decreased efficiency did not appear to be correlated with increases in radon mass loading, or retention of manganese, NPDOC, uranium or radium. The effect of bacterial growth on the GAC was not studied. The data suggested that iron precipitation in the GAC without pretreatment impeded radon sorption by fouling the GAC surface or causing channeling of water in the top of the bed. The gamma emissions data indicated that the zone of radon removal moved down the GAC bed over time. As a result, use of GAC systems in POE applications should be limited to raw water where the influent radon activity is low ( $\leq 5,000$  pCi/L). Under these conditions, the GAC should be able to produce effluent in the range of the proposed MCL (200-2,000 pCi/L).
2. When GAC is used for radon removal in small community applications, accounting for variations in water flowrate and raw water radon activity is crucial in design. In POE applications, these variables are somewhat less important, especially where the raw water has low to moderate radon activity because excess GAC can be supplied for the units with little extra cost. At higher loadings, however, the POE GAC units may not be able to dampen excess radon applied without some increase in effluent activity.
3. GAC systems in most POE applications will require either pretreatment and/or backwashing to prevent fouling resulting from accumulation of particulates, metal precipitates, bacteria or organic matter. Ion exchange pretreatment will be essential where iron and manganese concentrations in the raw water are high. However, there are serious problems with ion exchange because the resin, backwash water and regenerant brine may become contaminated with long-lived radionuclides and may require specialized handling and disposal. If frequent backwashing of the GAC unit and use of a sediment filter can control the accumulation of particulates and metal precipitates in the bed, ion exchange pretreatment should be avoided.
4. The GAC may retain longer-lived radionuclides, such as uranium-238, radium-226 and lead-210, in quantities which require disposal in a stabilized landfill or a low level radioactive waste facility. As a result, GAC may not be a viable radon removal technique for raw

water with high concentrations of uranium, radium or radon. A more thorough risk assessment and economic analysis should be conducted for applications where the raw water has low radon activities to determine whether the problems associated with disposal are outweighed by the benefits of GAC (e.g., cost, ease of operation and maintenance).

5. Gamma emissions from GAC beds were in the range of 2-3 mR/hr at the surface of the unit. Water jacket shielding only reduced the measured dose by 17%. However, Rydell et al. (1989) have shown that in POE applications where the influent radon activity is  $\leq 5,000$  pCi/L, the gamma emissions from the GAC will be greatly reduced to acceptable levels. In these applications, use of water jackets could be avoided making access to the unit easier.

#### AERATION UNITS

1. The bubble plate and diffused bubble POE units were very efficient (>99%) at removing radon from the water even at the relatively high activities used in this study ( $35,620 \pm 6,727$  pCi/L). They should be able to meet an MCL of 200-2,000 pCi/L in most cases, primarily because of the high air to water (A:W) ratios used. In addition, variations in influent radon activity and water flowrate can be handled without a significant increase in effluent radon activity. Though the A:W ratios are excessive for most POE applications, the blowers used in the units are the most cost effective based on overall efficiency.
2. One major problem associated with the aeration techniques is iron oxidation and precipitation. Even at concentrations  $<1.0$  mg/L, precipitates can form and accumulate in the units and/or be released in pulses to the residence when the unit is started to meet demand. In the diffused bubble unit, iron accumulation on the diffusers can cause a decrease in air flow. As a result, iron treatment will be required in almost all POE applications which use aeration techniques. Pretreatment with ion exchange creates problems with radionuclide retention and disposal. Post filtration with sand has been proposed, but needs to be evaluated before it is used to insure it is effective and does not have problems with radionuclide retention, and to determine the frequency of backwashing required.
3. The aeration units are more prone to having operational problems than the GAC units because they have more mechanical parts (e.g., pumps and blowers). These will require frequent maintenance to insure proper operation. In addition, the blowers and pumps are very noisy during operation and the low power cut-off feature which protects the secondary (jet) pump will require manual restarting in the event of pressure loss (e.g., due to power failure). These features may be viewed by the owners as a nuisance and lead them to bypass or disconnect the unit.
4. Frequent maintenance is essential to the proper operation of the aeration units. The air intake filters to the blowers should be cleaned frequently to maintain adequate air flow. There should be

gauges which the owner can monitor to insure the proper air pressure/flowrate is maintained. Addition of audible alarms to warn the owner of potential low air flow or pump failure is necessary. Soundproofing or placement in a remote location may be required to reduce the noise during operation. Directions for restarting in the event of a power failure should be clearly displayed. Finally, the units should provide easy access to the owner, so that they can be properly serviced as directed in the operation and maintenance manual.

5. Proper venting of the off-gas from the aeration units is important. As demonstrated in this study, the plume is diluted fairly rapidly. However, the off-gas stack should be vented above the roofline to prevent any radon from re-entering the home. Placement of auxiliary blowers may be required to produce adequate flow in these vent pipes.

#### OVERALL EVALUATION OF POE SYSTEMS

1. The total production costs for the GAC units were \$9.88/1000 gallons without pretreatment and \$13.40/1,000 gallons with pretreatment including disposal costs (assuming the GAC and ion exchange resin are low level radioactive wastes). The total production costs for the aeration systems were \$22.58/1000 gallons (diffused bubble) and \$26.74/1000 gallons (bubble plate). The aeration costs do not include auxiliary blowers for venting or air treatment. All production costs were derived for a flowrate of 1.02 m<sup>3</sup>/day and ~35,000 pCi/L influent radon activity. The production costs for the POE radon removal systems are high relative to public water supplies because (i) there is no economy of scale, and (ii) it is assumed individual homeowners will be purchasing single POE units unlike utilities which could purchase large quantities of POE units for a service area. Therefore, there will not be a quantity discount on the POE equipment for these individual well water supplies.
2. There were elevated levels of bacteria in the effluent from all of the units tested. Depending on EPA and state regulations, it may be necessary to disinfect the treated water before consumption.
3. Frequent monitoring of the effluent quality from any of the POE units should be stressed to the owner. Because radon cannot be readily detected by the senses, there is a potential for the water to be untreated if a POE unit fails without the homeowner being aware of the problem. Water analyses at the tap should be conducted frequently to avoid this problem.
4. At low influent radon activities ( $\leq 5,000$  pCi/L), GAC is the preferred treatment technique in POE applications where there are not excessive concentrations of long-lived radionuclides in the water. GAC is recommended because (i) it requires the least owner maintenance, (ii) is the easiest system to operate, and (iii) is the least expensive with respect to capital and operation and maintenance costs even considering disposal costs. At low mass loadings, achieving a high percent removal efficiency is less

critical, and the GAC can therefore meet an MCL in the range 200-2,000 pCi/L. In addition, at these levels gamma emissions are minimized. At higher mass loading rates, aeration techniques would be required to meet an MCL of 200-2,000 pCi/L.

## SECTION 3

### METHODS AND MATERIALS

This section describes the treatment systems and outlines the sampling and analytical methods used in the project. A summary of all data from the quality control checks made throughout the project is provided in Appendix A.

#### DESCRIPTION OF TREATMENT UNITS

##### Granular Activated Carbon POE Systems

The GAC systems were designed by Lowry Engineering (Unity, ME). Each GAC unit consisted of a cylindrical fiberglass contactor (I.D. = 24.8 cm, Height = 137 cm). A three way valve situated on the top of the unit controlled backwashing and bypassing. Barneby Cheney (Columbus, OH) Type 1002 activated carbon was used in both GAC units. The unit preceded by ion exchange pretreatment contained 0.0465 m<sup>3</sup> of carbon and the unit without pretreatment contained 0.0470 m<sup>3</sup> of carbon. The units were initially backwashed for 15 min to remove fines. Raw water entered the top of each unit and was distributed across the surface of the GAC. The treated water was collected at the bottom of each unit and flowed up a central PVC pipe and out of the unit.

Both GAC units were preceded by sediment filters designed to remove particulates from the raw water. These were manufactured by OMNI (Hammond, IA), and contained 24.5 cm long pleated paper filters (O.D. 6.5 cm) also manufactured by OMNI. The paper filters were replaced every 2-3 weeks.

An ion exchange unit (45,000 grains) manufactured by Lancaster Water Softener (Lancaster, PA) was installed between the sediment trap and the second GAC unit. The unit contained 0.042 m<sup>3</sup> of a strong cationic resin (Cybron C-249-sodium polystyrene sulfonate). It was designed to remove iron and manganese from the raw water before it entered the GAC. The unit was a 24.8 cm diameter (I.D.) and 119 cm tall fiberglass cylinder and was operated in a downflow mode. Regeneration with sodium chloride (brine) occurred every 2 weeks in the sequence shown in Table 2. The regeneration cycle was automated and recommended by the manufacturer.

##### Diffused Bubble Aeration POE System

The diffused bubble unit was designed by Lowry Engineering (Unity, ME) and was constructed of molded polyethylene. The unit consisted of three 46 cm (length) x 40 cm (width) x 24 cm (water depth) tanks in series, each of which contained an internal diffuser fed from a common header. All air piping was

TABLE 2. REGENERATION PROGRAM FOR THE ION EXCHANGE UNIT

Event	Time (min)	Flowrate (L/min)
Backwash	10	9.5
Brine* Regeneration	90	3.8
Rapid Rinse	10	9.5
Brine Refill	16	3.8

\* Brine was 180 g/L of NaCl.



constructed from PVC. The diffusers contained variably-spaced 0.64 mm diameter holes. Air to the diffusers was supplied by a 1.58 m<sup>3</sup>/min capacity blower (Gast; Benton Harbour, MI) with a 1.5 ft<sup>2</sup> polyester cloth intake filter. A pressure gauge located just downstream of the blower was monitored to indicate whether the air pressure exceeded the value recommended by the manufacturer ( $\leq 26$  in. H<sub>2</sub>O). [N.B., Greater air pressures indicated air flow out of the diffusers was restricted.] The exhaust collected in the top of the unit was vented outside using a 5 cm diameter PVC pipe fitted with a wire mesh to prevent animals from entering the exhaust pipe. Raw water was pumped into the first chamber of the diffused bubble unit directly from the well. The water flowed through the unit by simple displacement and was pumped (Myers; Ashland, OH; jet pump; 32 L/min) from the third compartment to a 76 L hydropneumatic tank. The solenoid valve, controlling the operation of the unit, was regulated by high and low water float switches located in the third chamber. A timer connected to the blower was set to insure that air flow continued 10 min after cessation of water flow to insure that radon was removed from all water remaining in the diffused bubble unit. A schematic of the diffused bubble unit is shown in Figure 1.

#### Bubble Plate Aeration System

The bubble plate aeration unit was designed by North East Environmental Products (West Lebanon, NH). It was housed in a 60 cm long x 38 cm wide x 23 cm high molded plastic casing with a central 10 cm diameter PVC vent pipe. Raw water entered the unit directly from the well and was distributed by a 0.95 cm spiral diffuser into a 7.6 cm wide channel constructed of polyethylene. The bottom of the channel was perforated by 4.8 mm diameter holes spaced 1.9 cm apart. During operation, air from a 535 m<sup>3</sup>/hr capacity EBM Industries (Unionville, CT) blower was forced up through these holes. The blower had a 200  $\mu$ m polyethylene foam filter in the air intake. The air caused the raw water column to rise to a total height of 17 cm. The off gas was vented out the top of the bubble plate chamber via the PVC exhaust pipe. The flow of water through the channels in the bubble plate unit is shown in Figure 1. At the end of the channel (length = 270 cm), the treated water flowed over a 7.6 cm weir and into a 39 cm (height) x 57 cm (length) x 57 cm (width) polyethylene holding tank located below the bubble plate. Water was pumped from the holding tank to a 76 L hydropneumatic pressure tank by a Jacuzzi 1/2 hp jet pump. The flow of water out of the bubble plate was regulated by a float switch in the holding tank connected to a solenoid valve. A timer connected to the blower was set to insure that air flow continued 1 min after cessation of water flow.

#### OVERALL SYSTEM DESIGN

The entire project was conducted at the Scobie Pond ground water well and pumphouse facility (Derry, NH) owned by Southern New Hampshire Water Company (Hudson, NH). The facility no longer serves the community so the raw water could be used for our study. Treated water was discharged to a nearby wetland area.

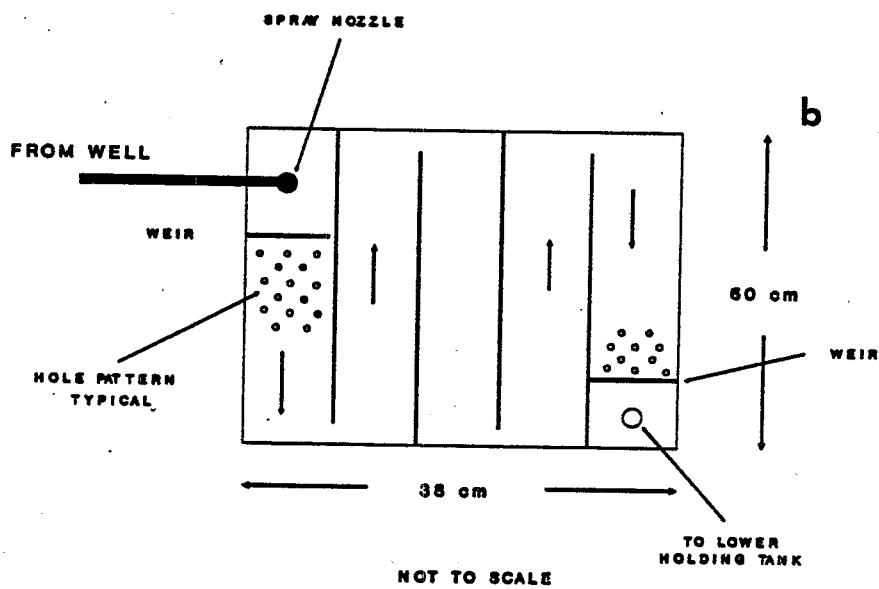
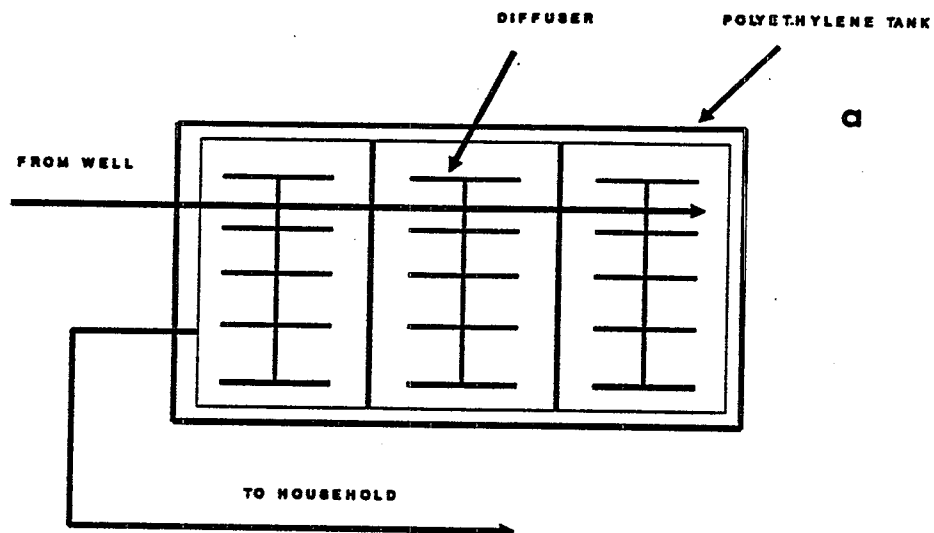


Figure 1. Schematics of the diffused bubble unit (a) and the bubble plate chamber (b). Not to scale.

At the beginning of the study, water was pumped from the wells with submersible pumps into a 0.95 m<sup>3</sup> polyethylene equalization tank. A 3/4 hp jet pump (Myers; Ashland, OH) supplied the raw water to the units (Figure 2). The tank was designed as an equalization basin for the raw water to dampen short-term changes in water quality. Use of this tank was discontinued after 2 months because iron was precipitating out of solution during storage. Two Amtrol (W. Warwick, RI) Well-X-Trol household hydropneumatic tanks, (76 L and 121 L capacity) were installed in place of the tank to equalize the flow to the units. Copper piping (1.9 cm ID) was used to plumb the entire system.

Samples were collected from seven different locations (Figure 2). Samples were collected from 1.8 cm brass valves using 1.27 cm (I.D.) clear polyethylene flexible tubing. All water flowed to a sampling board to facilitate rapid and efficient collection. Brass valves (1 cm I.D.) located on the sampling board were used to regulate flow into the 0.64 cm polyethylene tubing from which the samples were directly collected.

Approximately 1,022 L of water was distributed to the units each day in one 30 min and six 18 min sampling intervals using a Dayton Time Switch (Chicago, IL) (Table 3). The flowrate was adjusted to approximately 7.6 L/min using a CAL-Q-FLO rotometer (maximum capacity = 38 L/min) (Blue and White Industries; Westminster, CA) located on the influent lines to the GAC units and the effluent lines of the aeration units. These operating periods and flowrate conditions were chosen to simulate POE applications (Anderson and Watson, 1967). The volume of water treated during a sampling event and between sampling events was recorded using Hersey (Dedham, MA) MVR water meters, located on the influent lines for both GAC units and the diffused bubble unit and the effluent line for the bubble plate unit (Figure 2).

#### SAMPLING EVENTS

All systems were started on January 7, 1989. The units were monitored every 24 hr for the first three days of the study. The GAC units were analyzed every 3 to 4 days for the first month, weekly for the next 5 months, and biweekly for the remainder of the study. The aeration units were monitored weekly for the first 6 months and biweekly thereafter. During routine sampling of all systems, aliquots of water were collected and analyzed for radon, pH, alkalinity, turbidity, iron, manganese, calcium, microbial numbers, and temperature. The GAC systems were also sampled for uranium, radium and NPDOC. Data collection was completed on January 3, 1990.

#### Diurnal Variation Studies

The GAC systems were monitored during each operating interval for one day in February and one day in August to determine the effects of natural diurnal variations in loading on system performance.

#### Loading Rate Studies

A series of studies were conducted to evaluate the efficiency of the GAC systems during periods of increased loading. In the first study, the flowrate was held constant at 7.6 L/min, while the total daily throughput was increased

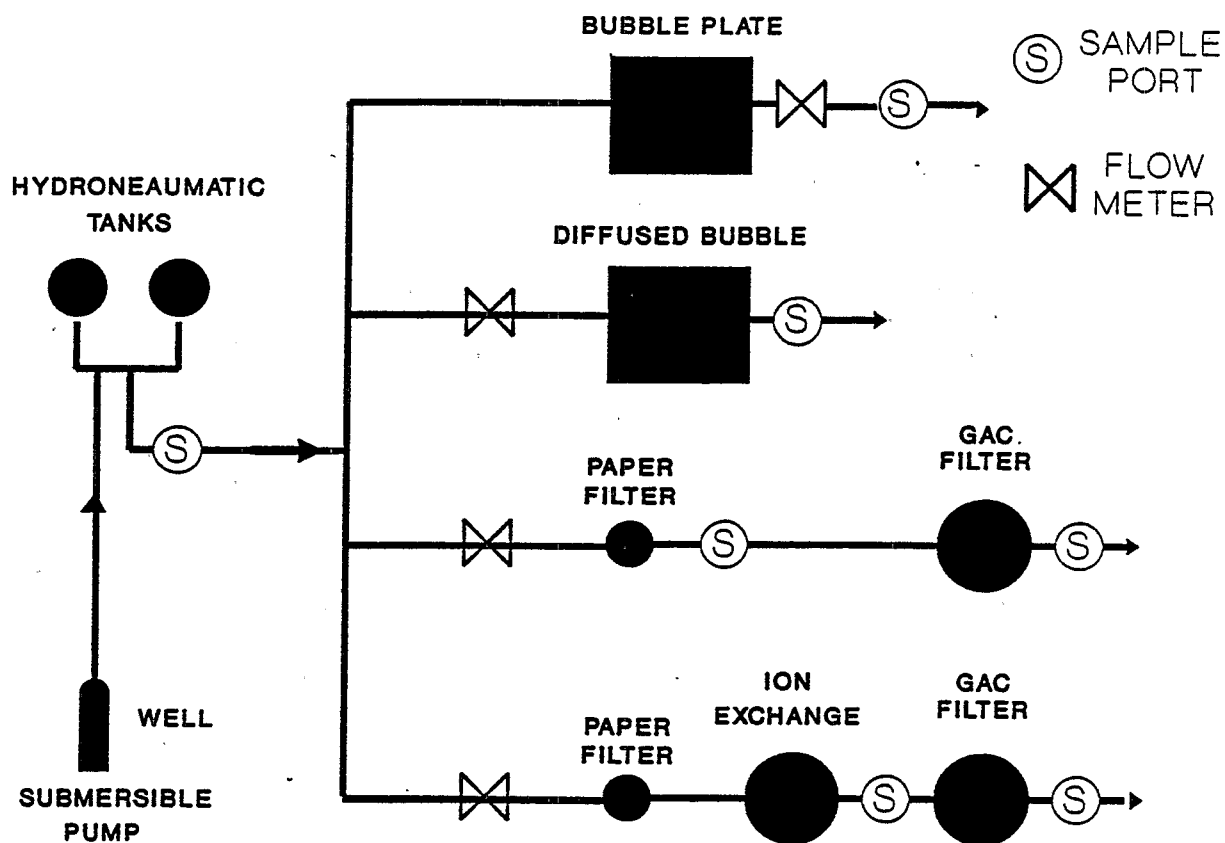


Figure 2. Schematic of the POE systems (not to scale).

TABLE 3. DAILY OPERATING SCHEDULE FOR THE POE UNITS

<u>Starting Time</u>	<u>Operating Time (min)</u>
6:30 a.m.	18
7:30 a.m.	18
8:30 a.m.	30
12:00 noon	18
5:30 p.m.	18
7:00 p.m.	18
9:10 p.m.	18

to 1,890 L. This was achieved by increasing the frequency of the 18 min loading intervals from 6 to 12. Two other studies were conducted by increasing the flowrate to ~20 L/min with a total daily throughput of 1,022 L (normal conditions) and 1,890 L, respectively. The loading rate tests were conducted one week apart, during the month of August and repeated again during October. Samples were collected at each operating interval throughout the day for all water quality parameters except uranium and radium during the August trials and for radon, pH, alkalinity, turbidity and total iron and manganese during October.

#### Backwashing

A study was conducted to determine if backwashing affected the performance of the GAC units. The manufacturer (Lowry Engineering) recommended a backwash flowrate of 19 L/min be used. However, this flowrate caused a loss of carbon from the unit, so the flowrate was lowered to approximately 7.6 L/min. This flowrate was maintained for 15 min, as recommended by the manufacturer, without noticeable loss of carbon. The GAC without pretreatment was backwashed during the last week of November and the GAC system with pretreatment was backwashed during the second week of December.

Samples for radon, turbidity, bacterial numbers, and total and soluble iron and manganese were taken before backwashing and 1, 3, 24 and 48 hours after normal operation resumed.

#### GAC and Ion Exchange Coring Study

Carbon samples were taken from the GAC units at the termination of study on January 3, 1990. Samples were collected at the top of the bed and at depths of 43 and 93 cm below the GAC surface for the unit without pretreatment. For the GAC preceded by pretreatment, samples were collected at the top of the GAC and at depths of 41 and 93 cm below the surface. Resin samples from the ion exchange unit were collected at the top of the resin and at depths of 38 and 76 cm below the surface. Solid carbon and resin samples were removed by cutting through the units at these depths with a reciprocating saw and sampling material not exposed to the blade. The samples were analyzed for iron, manganese, calcium, uranium-238, uranium-235, radium-226, lead-210, moisture content, and microbial numbers.

#### Gamma Radiation Shielding Study

At the end of the study, a water jacket, supplied by the GAC system's manufacturer, was placed around the GAC unit with pretreatment to investigate the effectiveness of water shielding in reducing gamma emissions. The jacket was composed of a polyethylene tank (61 cm diameter, 136 cm height) and provided a layer of water 30.5 cm thick around the entire GAC unit. Gamma emissions measurements were taken 30.5 cm and 150 cm away from the surface of the GAC unit before and after the jacket was filled with water. The measurements were taken at the top of the GAC bed and 41 and 93 cm deep within the bed.

## Air Monitoring

Alpha track detectors, type DF (Terradex Corp.; Glenwood, IL), were placed at various locations inside and outside of the pumphouse to measure potential increases in the radon activity in the air as a result of the release of radon from the aeration units. Four detectors were placed 135 cm beneath the (downward curved) vents from the aeration units. Four detectors were placed on each outside corner of the pumphouse roof. Ten detectors were placed at various locations in the wooded area surrounding the pumphouse (Figure 3) at heights of approximately 1.5 m off the ground. Two detectors were placed outside a residence approximately 5 km from the site to determine background levels of radon in the air in Derry, NH.

The detectors were placed inside 0.5 to 1.0 L inverted cans to protect them from precipitation. The cans were not sealed so the detector was directly exposed to the air. The detectors were installed on September 19, 1989 and removed on January 9, 1990. The alpha track detectors were analyzed in January 1990 by the manufacturer.

## SAMPLING AND ANALYTICAL TECHNIQUES

### Sampling Methods

Water samples for radon, temperature, pH, alkalinity, turbidity, total iron and manganese, soluble iron and manganese, calcium, NPDOC, microbial numbers, total uranium, and radium-226 were collected from the treatment systems at seven locations (Figure 2). Duplicate samples were collected for all analyses except total uranium, radium-226, and microbial numbers.

Water samples were collected directly from the plastic tubing connected to the sampling valves located in the POE treatment system. The flow exiting the tubing was controlled using brass valves attached to the sampling board. The entire POE system and all plastic tubing was allowed to flush for 10 min prior to sample collection, to insure that water which had been stagnant in the system prior to operation was removed.

Sample containers for temperature, pH, turbidity, alkalinity, dissolved oxygen, total iron and manganese, soluble iron and manganese, calcium, and NPDOC were cleaned by soaking in soapy water for 20 min, rinsing three times with deionized water, soaking for a minimum of 20 min in a primary cleaning solution (Table 4), rinsing three times with deionized water and once with double deionized water. The sample containers and caps were rinsed three times with sample water before collection.

Blanks were taken for all analyses by transporting a 7.57 L jug into the field. Blanks for microbial numbers were taken by transporting a 250 mL container of sterilized water into the field. Double deionized water was obtained by passing deionized water through a Milli-Q 4 bowl water system (Millipore; New Bedford, MA).

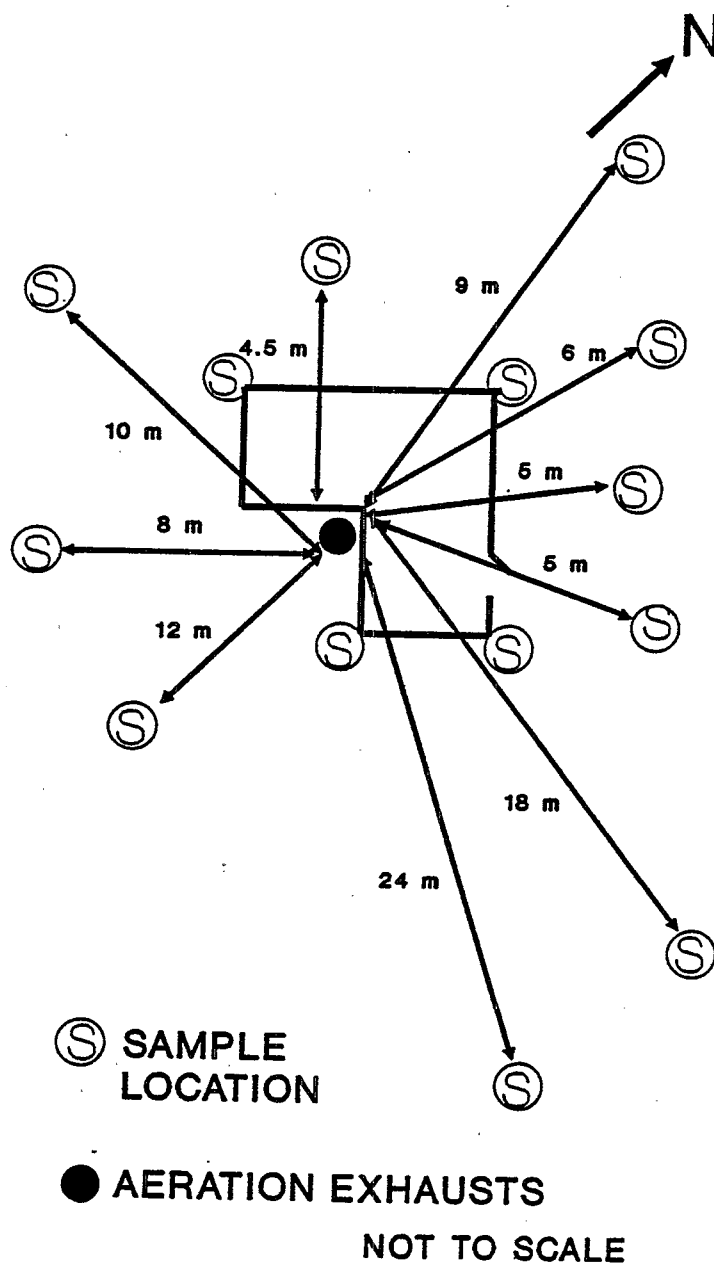


Figure 3. Schematic showing the locations of the alpha track detectors.



TABLE 4. SAMPLING MATERIALS PREPARATION AND PRESERVATION

Analysis	Container Volume (mL)	Material	Preparation (Primary Cleaning Solution)	Preservation	Hold Time
Radon	20	G*	10% Extran <sup>R</sup> (VWR Scientific)	None	4-12 hr <sup>+</sup> (in growth)
Temperature	250	P <sup>‡</sup>	50% HCl	None	None
NPDOC	20	G*	25% Chromic Acid	HNO <sub>3</sub> 0.15% (v/v)	2 wk
pH, Alkalinity and Turbidity	250	P <sup>‡</sup>	50% HCl	4°C (iced)	24 hr
Iron, Manganese, and Calcium	60	P <sup>‡</sup>	50% HNO <sub>3</sub>	HNO <sub>3</sub> 0.15% (v/v)	6 mo
Uranium, Radium	3785	P <sup>‡</sup>	50% HNO <sub>3</sub>	HNO <sub>3</sub> to pH<2	6 mo
Microbial Numbers	60	P <sup>‡</sup>	Sterilized Autoclaved 121°C @ 15 psig	4°C (iced)	24 hr

\*G = Glass.

<sup>+</sup>After extraction via shaking.<sup>‡</sup>P = Polyethylene plastic.

## Radon

Aqueous samples for radon were drawn from the polyethylene sampling tubes using a 10 mL Hamilton<sup>R</sup> gastight glass syringe fitted with a 13 gauge needle. The syringe was rinsed three times with the sample water before collection. A 10 mL sample, devoid of air bubbles, was slowly injected into a 20 mL glass low absorbance scintillation vial (Wheaton; Millville, NJ) below the surface of 10 mL of a toluene-based liquid scintillation cocktail [40.3 mL Liquifluor (Dupont; Wilmington, DE) per 1 L of scintillation grade toluene].

The samples were analyzed after radon came to secular equilibrium with its short-lived progeny (preliminary experiments indicated we should wait 4 hrs after collection) and before 12 hr had elapsed between collection and analysis. Radon samples were analyzed using a Beckman (Fullerton, CA) LS 7000 liquid scintillation counter (LSC). The manufacturer's program 6 was used for all analysis (Appendix B). A counting time of 10 min was used for all analyses except for the effluent samples taken from the aeration units. The counting time was increased to 50 min on these samples because of their low radon activities. Automatic quench compensation was used with a cesium-137 source. The instrument was calibrated with Beckman tritium, carbon-14 and background sealed standards. The efficiency factor (E) for the instrument was determined daily using 10 radium-226 standards ranging in activity from 6,500 to 65,000 pCi/L. The data obtained from these standards was used to make a linear standard curve. The efficiency factor (E) was calculated from the slope of the line-of-best fit for the data through the origin. The LSC provided results in counts per minute (cpm) for two windows: Channel 1 = 0 - 397 (corresponding to a full tritium channel) and a Channel 2 = 397 - 940 (a tritium - phosphorus-32 channel). The majority of the counts from radon-222 and its progeny were located in the Channel 2 pulse heights. The total counts (Channel 1 and 2) for each sample were then converted to pCi/L using the equation:

$$A = \frac{(C_s - C_b) \times 1000 \text{ mL/L}}{(E)(V)(D)} \quad (\text{eq. 1})$$

where: A = radon activity (pCi/L)  
C<sub>s</sub> = cpm of the sample  
C<sub>b</sub> = background cpm of field blank (cpm)  
E = efficiency factor (cpm/pCi)  
D = decay correction factor  
V = sample volume (mL)

The decay correction was determined from:

$$D = e^{-0.693(T)/t_{1/2}} \quad (\text{eq. 2})$$

where: T = time from sampling to counting (days)  
t<sub>1/2</sub> = half-life of radon (3.82 days)

Duplicate samples were analyzed every tenth sample to determine precision. The radium-226 standards and field blanks were counted at the beginning of each analytical run.

The radium-226 standards were prepared from National Bureau of Standards (NBS) or EPA (Environmental Monitoring Systems Laboratory; Las Vegas, NV) primary standards. The standards, which came in glass ampules, typically contained 5 g of an HCl solution with radium-226 activities ranging from 4 to 5 nCi/g. The contents of the ampule were emptied into a 50% HNO<sub>3</sub> washed and air dried, glass beaker to facilitate weighing in a Mettler AC-100 analytical balance. The contents of the beaker were then transferred to a 200 mL volumetric flask (cleaned using 10% Extran<sup>R</sup>, 50% HNO<sub>3</sub> and double deionized water) and the beaker was rinsed several times with 0.05M HNO<sub>3</sub> to insure all radium-226 was transferred. The stock radium-226 solution was prepared in a balance of 0.05M HNO<sub>3</sub>. It was stored in the wax-sealed 200 mL volumetric flask at 4°C. The stock solution usually contained 117.5 pCi/mL (260.85 dpm/mL) of radium-226. The appropriate volume of the stock solution required to make the standards was added to a clean scintillation vial using a volumetric pipette and was diluted with 5 mL of 0.05M HNO<sub>3</sub>. The contents of the vial were purged for 20 min with fine bubbles of laboratory-grade nitrogen gas. Subsequently, 10 mL of the toluene-based scintillation cocktail were slowly added to the standard. The scintillation vial was sealed and counted daily on the LS 7000 to determine when the radium-226 was in secular equilibrium with radon-222 (~20-25 days). New standards were prepared every 3 months. Once the standards were in secular equilibrium, they were used for ~4 months. If the cpm of the radium standards began to change before that time, they were no longer used.

#### Temperature

Temperature was obtained by using Fisher (Boston, MA) Model 14-983-17A mercury thermometers (Range -20 to 110°C). The thermometer was immersed into 250 mL bottles containing sample water for NPDOC and soluble metals immediately after collection. The reading was taken after the thermometer equilibrated (~1-3 min).

The accuracy of the field thermometers was checked monthly against an ASTM-approved mercury thermometer using boiling water and ice baths. Readings on the field thermometer were corrected, as needed.

#### pH

Samples for pH were collected in 250 mL polyethylene bottles. The pH was measured immediately after arrival at the laboratory with a Beckman (San Ramon, CA) Altex 71 pH meter connected to a combination gel pH electrode and a temperature compensation probe. The meter was calibrated with two VWR Scientific (Boston, MA) pH standards (pH = 4 and 7), as outlined in Section 423 of Standard Methods (1985). The drift of the instrument was checked by analyzing the standards every 20 samples or every hour, whichever came first. If one or both of the standards did not read within 0.1 pH units of the original value, the meter was recalibrated and the samples were reanalyzed.

The precision of the meter was checked every fifth sample. The accuracy of the meter and calibration method were checked monthly with two NBS pH standards (pH = 4 and 6.8). Action was taken to repair the meter or replace the working standards if the measured value differed by more than 0.1 pH units from the NBS standards.

#### Alkalinity

Alkalinity was determined potentiometrically as outlined in Section 403 of Standard Methods (1985). The initial pH of the sample was recorded before the sample was titrated against 0.02 N  $H_2SO_4$ . The titration was continued until the pH of the sample dropped into the pH range of 4.4 - 4.6. The final pH of the sample was recorded after the titration was completed. Alkalinity (mg/L as  $CaCO_3$ ) was determined from the following equation:

$$\text{Alkalinity} = \frac{A \text{ N (50,000)}}{\text{mL of sample}} \quad (\text{eq. 3})$$

where A is the volume (mL) of titrant used and N is the normality of the titrant. The normality of the titrant was determined monthly using a  $Na_2CO_3$  primary standard. The precision of the analysis was checked every fifth sample. If the precision exceeded the control limit of  $\pm 5$  mg/L as  $CaCO_3$ , all previous analyses were repeated.

#### Turbidity

Samples for turbidity were analyzed on a Hach<sup>R</sup> (Loveland, CO) Model 2100A turbidimeter, using the method outlined in Section 214 of Standard Methods (1985). The instrument was calibrated with secondary-sealed standards supplied by Advanced Polymer Systems (Redwood City, CA). The calibration was checked between each sample. Precision quality control charts were developed prior to the beginning of the project using the method outlined by Standard Methods (1985). Duplicate analyses were performed every fifth sample to check precision. If the value of precision was unacceptable (as based on QA/QC criteria - see Appendix A), all previous samples were reanalyzed. Turbidity samples from the EPA water supply performance evaluation study were analyzed to determine the accuracy of the analysis.

#### NPDOC

Aliquots for NPDOC were taken from the 250 mL polyethylene bottles containing the sample using a 60 mL Luer-Lok<sup>R</sup> plastic syringe (VWR Scientific). The samples were filtered through water-washed GF/C filters into 20 mL glass VOA vials fitted with teflon septa. The syringes were cleaned in the same manner as the glassware (Table 4), except the syringes were rinsed with the primary cleaning solution (chromic acid) and not soaked.

The NPDOC samples were analyzed on a Dohrmann (Rosemont Analytical; Santa Clara, CA) Model DC-80 total organic carbon analyzer, using the UV-persulfate oxidation method outlined in Section 505b of Standard Methods (1985). Every sample was analyzed in duplicate after it had been purged for 5 min. Before each analysis, 5 potassium hydrogen phthalate standards were prepared to

develop a calibration curve for the instrument (range = 1-5 mg/L). A 1 mg/L EDTA standard was analyzed during each analysis to determine the accuracy of the calibration.

### Metals

Samples for total iron, total manganese and total calcium were collected in 125 mL polyethylene bottles. Immediately after collection, the samples were acidified with 180  $\mu$ L of  $\text{HNO}_3$  (final concentration = 0.15% (v/v)  $\text{HNO}_3$ ).

Samples for soluble iron and soluble manganese were collected in 250 mL polyethylene bottles. Approximately 60 mL was drawn from these containers using 60 mL VWR plastic syringes, and filtered through 0.22  $\mu$ m filters into 125 mL polyethylene bottles. The same filter was used for a duplicate set of samples. The 125 mL bottles containing 60 mL of filtrate were acidified to a final concentration of 0.15% (v/v)  $\text{HNO}_3$ .

An influent sample and a sample of blank water were spiked in the field for both total and soluble metals to check accuracy. Fisher Scientific 1000 ppm stock solutions were used to spike samples for iron and manganese. A 100,000 mg/L stock solution was prepared from calcium chloride, to spike samples for calcium analyses.

The metals were analyzed on a Perkin Elmer (Norwalk, CT) Model 2380 flame atomic absorption spectrophotometer (AAS) using an air acetylene flame and a 10 cm burner head. The samples were analyzed according to the procedure outlined in Section 303A of Standard Methods (1985). A calibration curve was developed, using 4 to 5 standards spanning the linear range of each metal. The standards were prepared daily from Fisher Scientific 1000 ppm stock solutions. Initial experimentation indicated that neither the method of standard additions nor the addition of calcium solution to the iron and manganese samples (Standard Methods, 1985) was required to overcome matrix problems or reduce ionization interferences. A lanthanum oxide solution (Standard Methods, 1985) was added to all samples being analyzed for calcium. Calibration standards were analyzed every tenth sample to check the drift of the instrument. The field spikes were analyzed every ninth sample to determine percent recovery and were compared with control chart specifications. If the value exceeded the control limits, all previous samples were reanalyzed. Precision was monitored every fifth sample. At the end of each set of analyses, the calibration standards were reanalyzed.

GAC and resin samples collected for metals analyses during the coring experiment were dried to a constant weight at 60°C. Two subsamples (2g) were placed in tared 125 mL polyethylene bottles and weighed on a Mettler AC-100 analytical balance. The samples were then digested in 50 mL of 10%  $\text{HNO}_3$  in a water bath at 60°C for 24 hrs (Lessard, 1987). The supernatant was decanted and filtered through double deionized washed GF/C filters and diluted to 100 mL in a volumetric flask. The liquid was analyzed using the AAS according to the methods outlined above.

### Microbial Numbers

Water samples for subsequent plating were collected in 60 mL polyethylene bottles. The bottles were cleaned by soaking in a low phosphate soap for 20 min, rinsing three times with deionized water and autoclaving for 15 min at 121°C and 15 psig. Sterilized double deionized water was transported to the field in a sterilized 250 mL polyethylene bottle. A sample of this sterilized water was analyzed as a control.

Microbial numbers were determined using the heterotrophic plate count technique outlined in Section 907 of Standard Methods (1985). Aseptic techniques were followed throughout the entire procedure (Methods 907 and 907B). A 0.1 mL aliquot was pipetted onto a low nutrient R2A agar (Difco; Detroit, MI) and incubated at 10°C for 11 days. All samples were plated in triplicate. Initially, dilutions of  $10^{-1}$  and  $10^{-2}$  were used, but  $10^{-2}$  was later found to be unnecessary. The incubation temperature and time were determined in preliminary experiments to yield the maximum number of organisms. The number of colonies (between 20 and 200) were recorded and the results were converted to colony forming units (CFU) per 100 mL. Sterile controls were run with every set of samples to check aseptic technique.

GAC and resin samples for microbial numbers from the coring experiment were stored for 20 hr at 4°C prior to analysis. Aliquots of the solid matter (5g) were placed in tared, sterilized beakers and weighed on a Mettler AC-100 balance. A 45 mL portion of sterilized 0.1% sodium pyrophosphate was added to each of the beakers. The samples were then sonicated for 30 min. Serial dilutions of the supernatant ( $10^{-3}$  to  $10^{-9}$ ) were plated in triplate on R2A agar and analyzed as outlined above.

### Uranium, Radium and Lead

Aqueous samples for uranium and radium analyses were collected in 3.79 L polyethylene containers and immediately acidified to a pH <2 with concentrated  $\text{HNO}_3$ . The samples were analyzed for total uranium and radium-226 by the State of New Hampshire's Environmental Services Laboratory (Concord, NH). Total uranium alpha activity was measured by the coprecipitation technique (Method 908.0) outlined by EPA (1980) using a Ludlum (Sweetwater, TX) 1000 scaler and a Ludlum 43-10 detector. Radium-226 activity was measured by the radon emanation technique (EPA, 1980; Method 903.1), using a Lucas scintillation cell and a Ludlum 1000 scaler equipped with a M-182 detector. A trace spike of barium-133 was added to all radium samples for determination of percent recovery.

Solid GAC and resin samples from the coring equipment were dried to a constant weight at 60°C. Aliquots of 2-3 g were placed in tared, plastic containers and weighed on a Mettler AC-100 analytical balance. The samples were counted on a Canberra high resolution gamma spectrometer with a coaxial Ge diode well detector (Model GCW 1022-7500). The readings were processed with a multi-channel-analyzer (Model 35). Standards to calibrate the instrument were made with lead-210 and virgin GAC and resin samples. Aliquots of virgin GAC and resin were counted to determine background readings for the instrument. Data was reduced to activities of uranium-238, uranium-235,

radium-226 and lead-210 per kg by the method presented by Larsen and Cutshall (1981).

#### Gamma/Beta Radiation Emissions

Gamma/beta emissions were taken by placing the detector of a Ludlum (Sweetwater, TX) Model #9 Micro R survey meter on the surface of the treatment units or holding it exposed to the air. The meter was set to record mR dose rate per hr. Measurements were taken at various locations in and around the pumphouse (Figure 4). Measurements were taken on the surface of the GAC contactors at four different locations (Table 5). The meter was calibrated every 6 months with a cesium-137 source by the University's radiation safety officer.

#### Percent Moisture Content

GAC and resin samples collected during the coring experiment were dried to constant weight at 60°C to determine percent moisture. Samples were placed in tared aluminum dishes and reweighed after cooling in a dessicator until a constant weight was attained. The percent moisture was calculated by dividing the final mass by the initial mass. The percent moisture was used to adjust wet weight to dry weight.

#### DATA ANALYSIS

All data were analyzed using Student's t tests (Miller and Miller, 1984) at  $\alpha$  values of 0.10, 0.05 and 0.01. The most rigorous  $\alpha$  value of the three at which the stated trends occurred is reported for each data set tested.

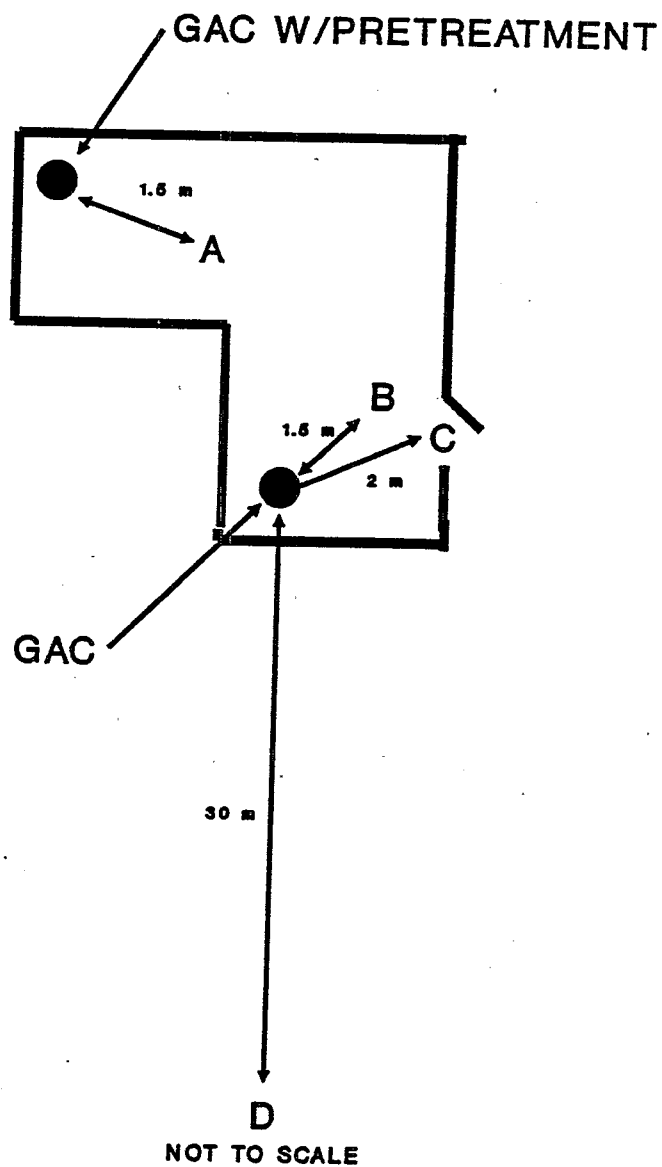


Figure 4. Schematic of the pump house showing the locations of the gamma emissions measurements (A,B,C, and D are locations where measurements were taken).



TABLE 5. LOCATIONS OF SURVEY METER MEASUREMENTS ON THE SURFACE OF GAC UNITS

Sample	<u>Depth Below GAC Surface (cm)</u>	
	GAC Without Pretreatment	GAC With Pretreatment
Top	1.5	0
Middle	43	41
Bottom	93	93

## SECTION 4

### RESULTS AND DISCUSSION

All of the treatment systems were put on-line on January 7, 1989 treating an influent resulting from a combination of ground water from 2 wells. The raw water to the treatment systems was found to vary frequently with respect to radon and other water quality parameters such as iron. This variation resulted from the differences between the raw water quality of the 2 wells and because of iron precipitation occurring during storage in the polyethylene tank. Therefore, in late April, the system was replumbed so that only 1 well was used and the water flowed directly from the well to 2 hydropneumatic tanks instead of the atmospheric storage basin. These modifications minimized differences in the raw water quality going to the individual treatment systems. A summary of all of the raw water characteristics is found in Appendix C. All of the systems were operated until December 1989 without major interruption in service. During December, there were several very cold days and on two occasions the plumbing froze and flow was stopped. In addition, during this period flow to the GAC system with pretreatment was stopped for 5 days while a treatment system for another project was installed. During the year of operation, there were several problems with the bubble plate's mechanical systems and plumbing. As a result, it was inoperable on a few occasions. In addition, the diffused bubble unit had a mechanical failure in late November and was not repaired because the study was almost complete.

Sampling was conducted weekly from January through June and biweekly thereafter. All special sampling events on the GAC systems (backwashing, coring, loading rate studies) were conducted during the latter half of the year. Air monitoring with the alpha track detectors was conducted from September through January.

The data obtained for each unit were compared with respect to the following parameters: water flowrate, temperature, pH, alkalinity, calcium, turbidity, iron, manganese, microbial numbers, NPDOC, radon, uranium, and radium. Analysis of the non-radioactive constituents allowed us to determine how the units were operating compared to similar systems treating other ground water contaminants.

#### WATER FLOWRATE

The Derry POE radon treatment system was constructed so that each unit produced enough water to meet a demand of 7.6 L/min at six 18 min intervals and one 30 min interval over the day. It is important to note that the flowrate into the two aeration units was in the range of 19 to 26 L/min, so that these units operated intermittently to meet the 7.6 L/min demand. Each unit had its own flow regulator. As a result, the actual flowrate through

each unit differed slightly at each sampling period (Figure 5). However, over the course of the study, there was no significant difference ( $\alpha = 0.10$ ) in the water flowrates treated by each unit. The overall flowrates for the units during the study are shown in Table 6 and were similar to the design value of 7.6 L/min typical of the demand in a residence (Anderson and Watson, 1967).

#### TEMPERATURE

The temperature of the raw water followed a seasonal pattern increasing in the spring and summer months and decreasing in the late fall and winter (Figure 6). This was similar to the results obtained in the small community radon removal project (Kinner et al., 1990). The temperatures of the raw water remained in a relatively small range (8°-17°C), typical of northern New England ground water (Johnson, 1975).

#### pH

The influent pH to the units averaged  $6.24 \pm 0.19$  during the first 4 months of the study. In late April, it decreased to 5.25 when the system was replumbed with one well and continued at that level for the remainder of the project averaging  $5.84 \pm 0.33$ . The pH of the water did not change significantly as it passed through the GAC units (Figure 7). During the study of GAC systems treating small community ground waters contaminated with radon (Kinner, et al., 1990), a dramatic increase in pH was observed in the first several days of operation. The increase in pH was also observed for the POE GAC units and was probably caused by dissolution of  $\text{CaCO}_3(\text{s})$  from the coconut shell-based carbon. However, because of the small amount of GAC used in the POE units, alkaline material leached out (solubilized) rapidly and after the first few days of operation, effluent pH was no longer affected by the GAC.

The pHs of the effluents from the aeration units (Diffused Bubble =  $7.27 \pm 0.38$ ; Bubble Plate =  $7.24 \pm 0.36$ ) were not significantly different from each other ( $\alpha = 0.10$ ). However, the effluents from both units were significantly higher than the influent ( $\alpha = 0.01$ ) by approximately 1 pH unit. This same level of increase was observed consistently even when the influent pH decreased in late April after the system was replumbed. A similar increase was observed in pH through the packed tower and diffused bubble systems during the small community radon treatment project (Kinner et al., 1990). The aeration process in the POE bubble plate and diffused bubble units probably increased the pH by removing  $\text{CO}_2$  from the water. Even though the pH was raised significantly, the resulting effluent pH was still in the acceptable range (6.5-8.5) for drinking water.

#### ALKALINITY

During the period from January to May, there were large variations in the alkalinity of the raw water. This occurred because each of the 2 wells used during this period had a different alkalinity. However, the influent alkalinity was still highly variable when only one well was used, especially during the period from August through October (Figure 8).

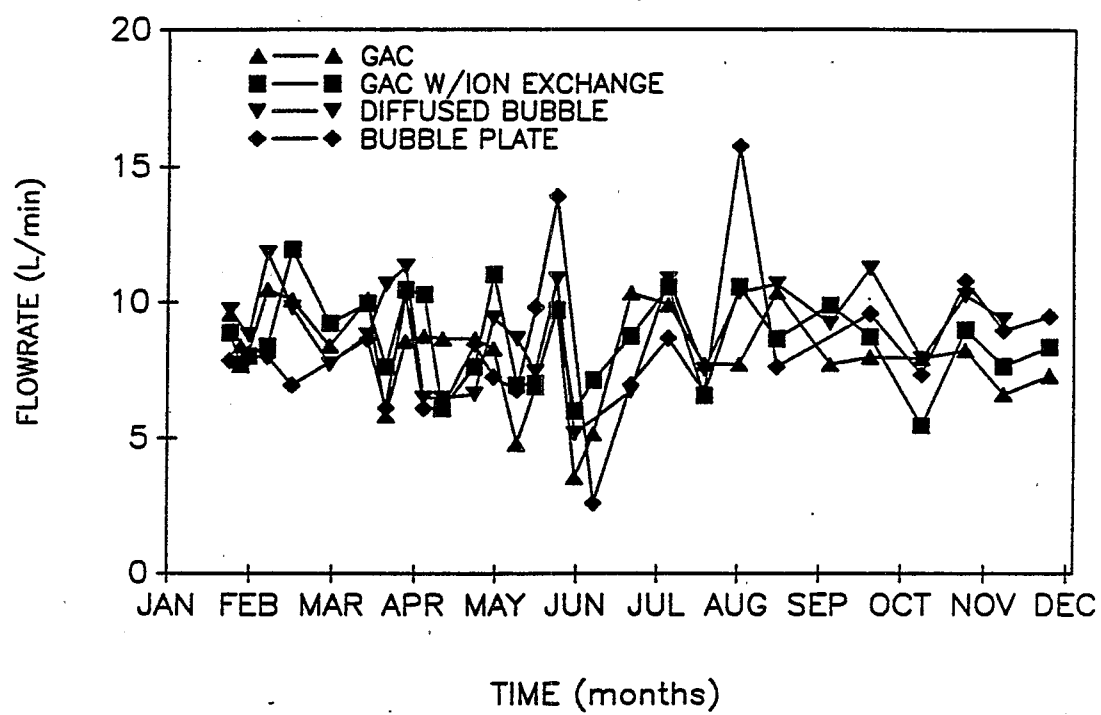


Figure 5. Water flowrate for the POE treatment systems.

TABLE 6. MEAN WATER FLOWRATES FOR THE POE TREATMENT UNITS

Treatment Unit	Water Flowrate (L/min)	
	Mean	Standard Deviation
GAC without Pretreatment	8.13	1.59
GAC with Pretreatment	8.62	1.53
Bubble Plate	8.08	2.33
Diffused Bubble	9.01	1.77

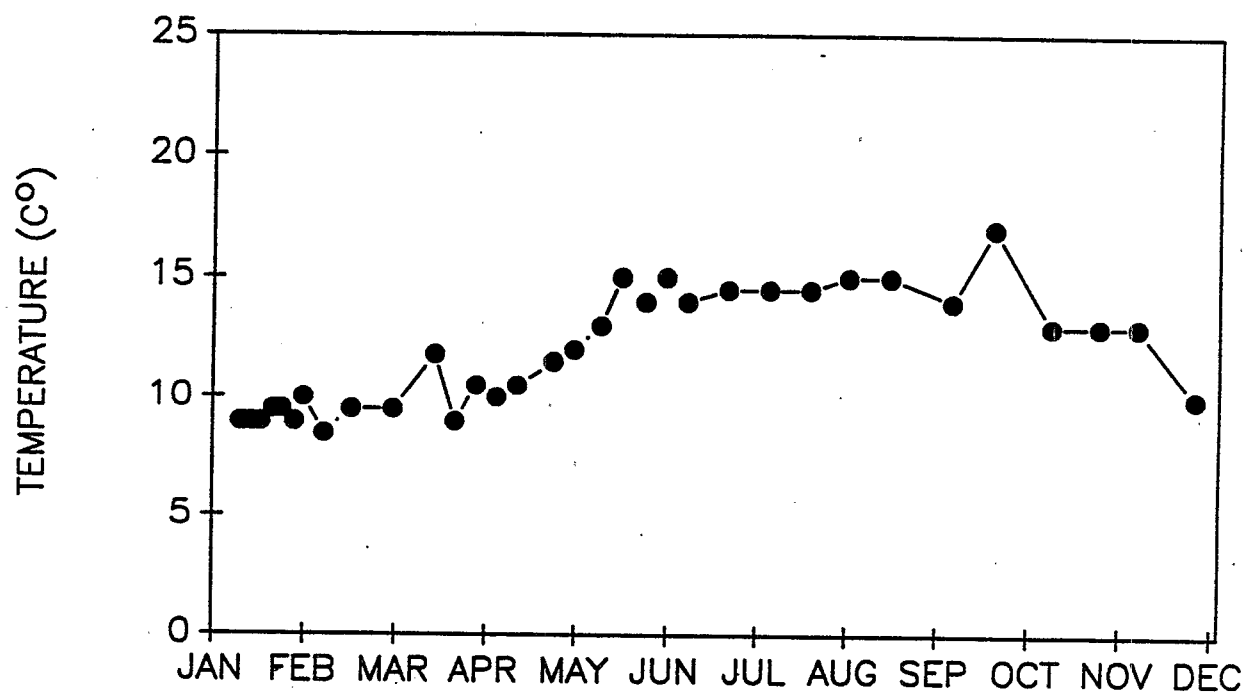


Figure 6. Temperature of the influent water.

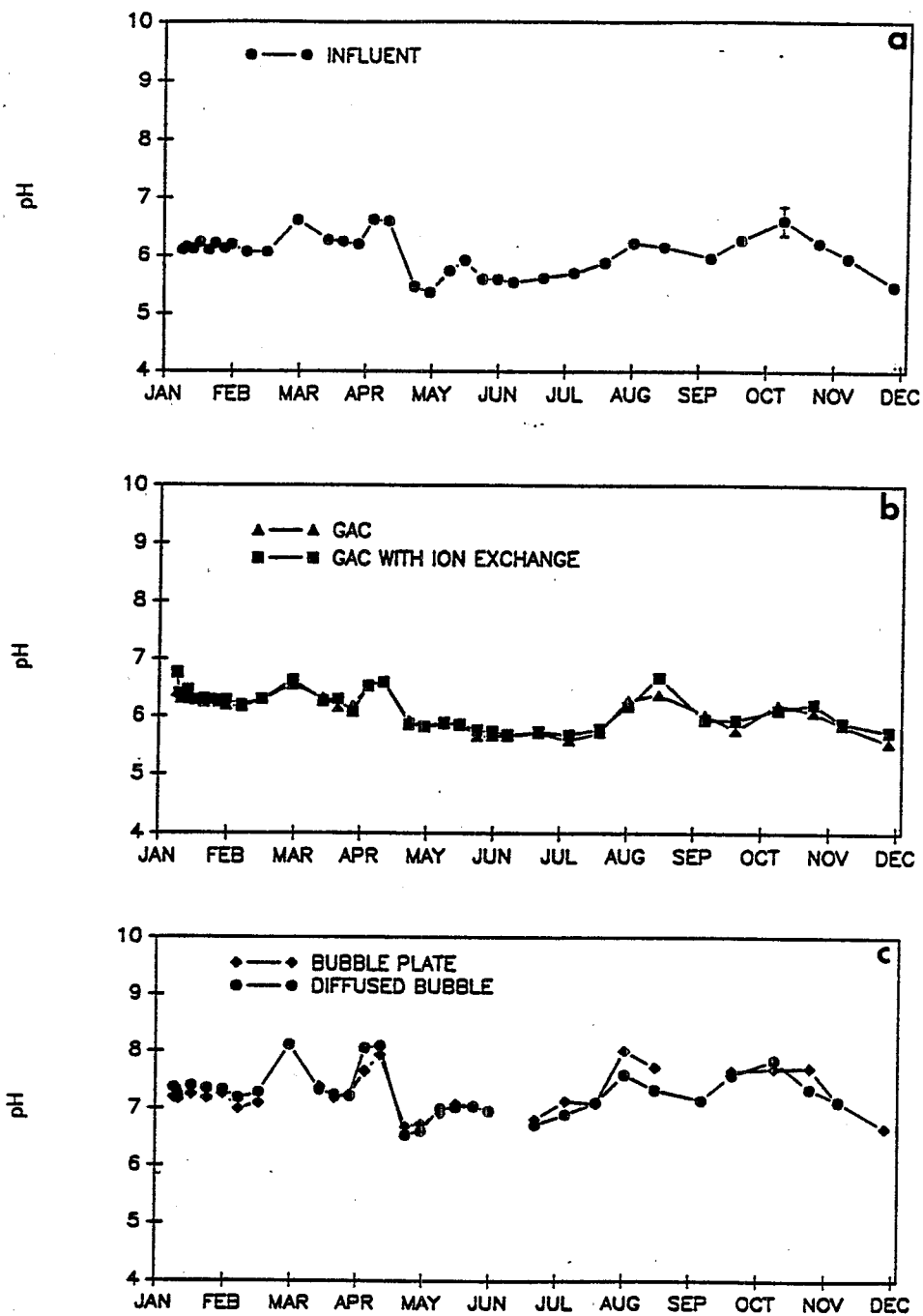


Figure 7. pH of the influent water (a), and effluents from the GAC systems (b) and aeration systems (c).

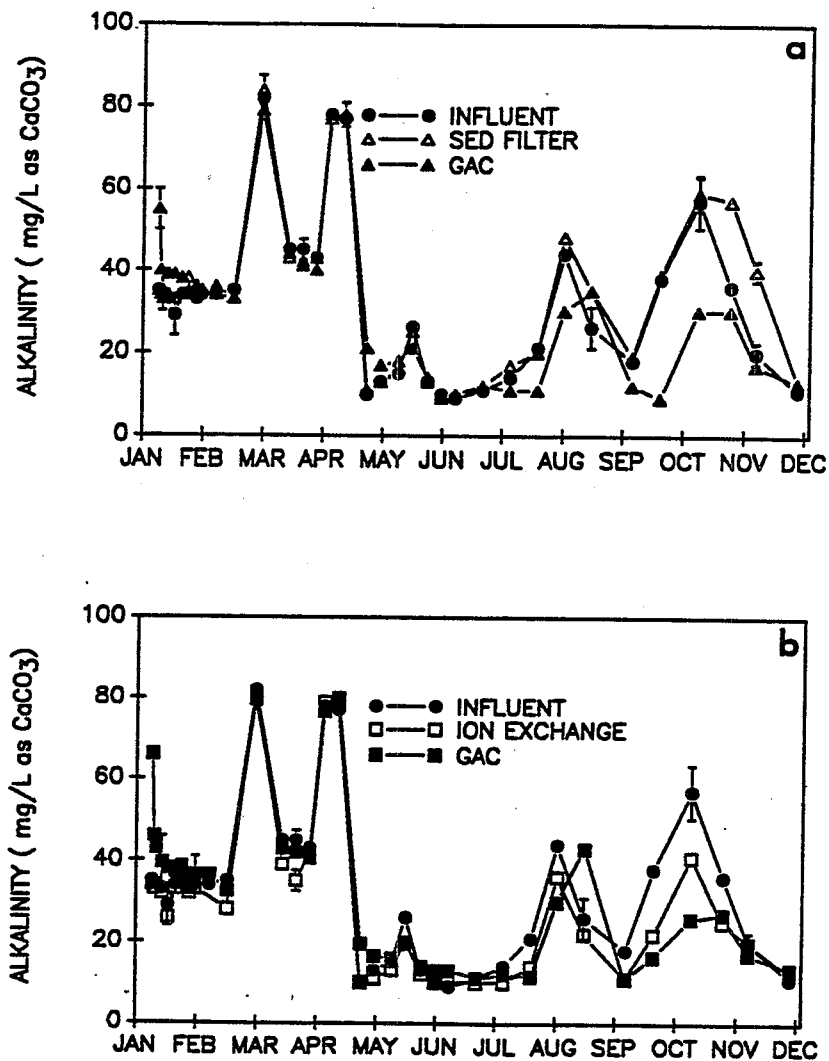


Figure 8. Alkalinity for the GAC without pretreatment (a) and the GAC with pretreatment (b).



Prior to June 1989, there was no change in the alkalinity of the water as it passed through the GAC systems (Figure 8). The one exception to this occurred during the first day of operation when the alkalinity in the GAC effluents was dramatically increased. This increase probably resulted from the dissolution of the  $\text{CaCO}_3(\text{s})$  from the GAC similar to the effect observed for the pH. An increase in alkalinity also occurred initially in the small community radon treatment study (Kinner et al., 1990).

During the period from mid-July until December, the water exiting both GAC systems was lower in alkalinity than the influent though not significantly ( $\alpha = 0.10$ ) when all of the data was pooled. The decrease in alkalinity may have resulted from release of  $\text{CO}_2$  by microorganisms growing within these units or by sorption of calcium species to the GAC. A similar decrease in alkalinity has been reported by Hubele and Sontheimer (1984) and Eberhardt (1976) for biological activated carbon. This hypothesis is supported by the microbial enumeration data which indicated bacteria were present in the GAC systems and by the calcium data which decreased through the GAC unit without pretreatment. However, calcium was not detected (detection limit = 14 mg/kg dry weight GAC) on the GAC obtained during the coring experiments. It is doubtful that microbial  $\text{CO}_2$  evolution would have resulted in a decrease in pH in these units because they were fairly well buffered (mean alkalinity = 28-34 mg/L).

There was no significant difference ( $\alpha = 0.10$ ) between the influent and effluent alkalinity for the bubble plate unit (Figure 9a). A similar trend was observed for the diffused bubble unit (Figure 9b). However, during the last half of the study, there was a small decrease in the alkalinity of the water as it was treated by the diffused bubble unit. During this same period, there was substantial iron precipitation and microbial activity. Either of these conditions may have increased the acidity of the water in the unit causing the decrease in alkalinity observed. The water was probably still buffered well enough, however, to prevent any significant change in pH.

#### CALCIUM

During the first 4 months of operation, the calcium concentration in the raw water averaged  $15.5 \pm 1.15$  mg/L as  $\text{CaCO}_3$  (Figure 10). Calcium concentrations did not vary as greatly as the alkalinity data did over the same period. During the last 6 months of the study, the raw water calcium and alkalinity concentrations showed similar trends.

A small amount of calcium was removed by the GAC unit without pretreatment (Figure 10a) from July through November and this corresponded to the removal of alkalinity occurring in that unit. The adsorption of calcium by the GAC is consistent with other studies that report calcium accumulation in GAC columns (Alben et al., 1983). The ion exchange unit removed all of the calcium from the raw water and thus the subsequent GAC unit did not receive any measurable input of calcium (Figure 10b). Analysis of the carbon samples from the coring experiment indicated that no detectable amount of calcium was retained in either GAC unit (analytical detection limit = 14 mg/kg dry weight of GAC).

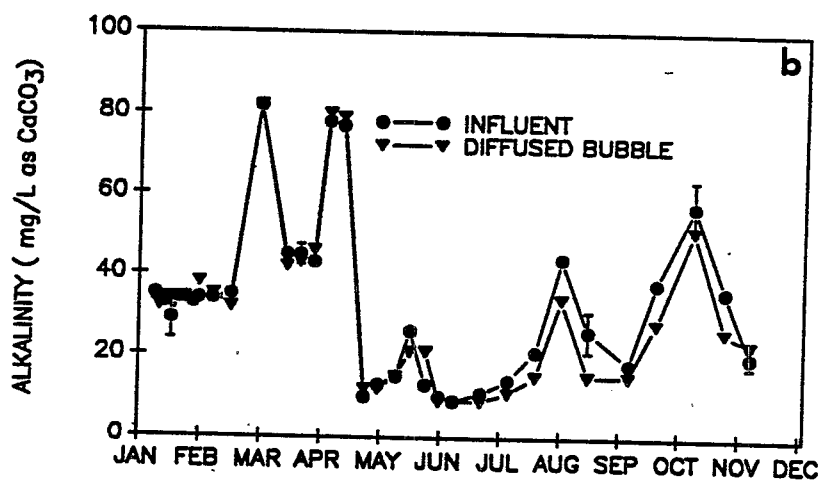
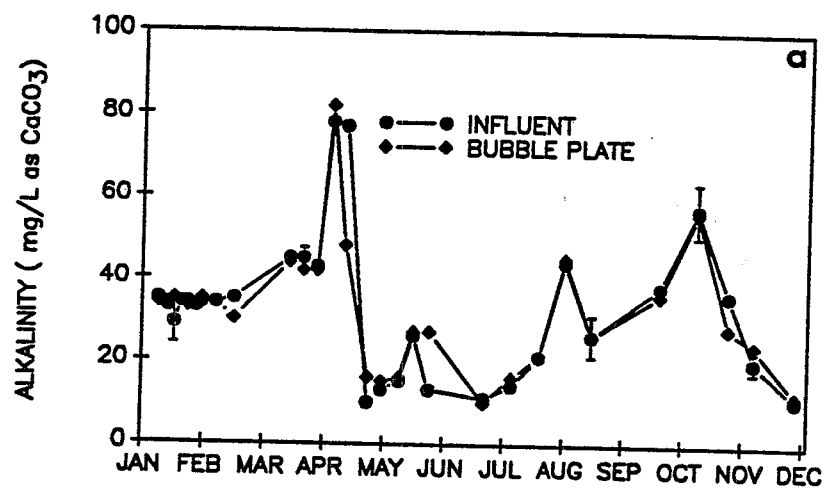


Figure 9. Alkalinity for the bubble plate unit (a) and diffused bubble unit (b).

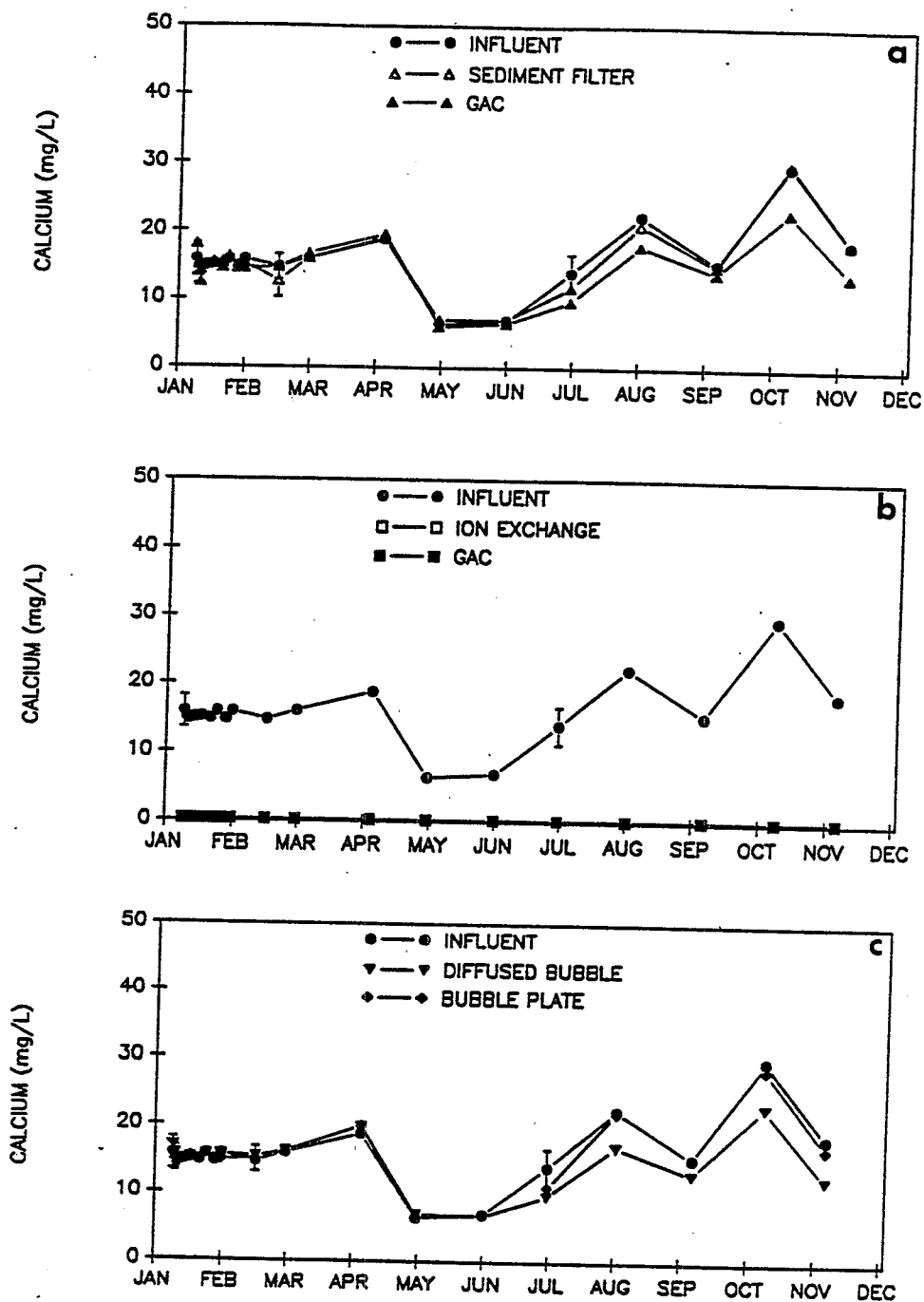


Figure 10. Calcium for the GAC without pretreatment (a), the GAC with pretreatment (b), and aeration systems (c).

There was no significant change in the calcium concentration of the water when it was treated in the two aeration units ( $\alpha = 0.10$ ) (Figure 10c).

## TURBIDITY

The raw water at the site varied between 0.13 and 4.1 NTU over the course of the study (Figure 11). During the initial months of operation, the variable, but relatively high level of turbidity was probably the result of particulate iron in the influent water. During this period, raw water was held in an atmospheric storage tank where iron precipitation was occurring. When the system was replumbed by replacing the storage tank with 2 hydropneumatic pressure tanks in late April, there was a decrease in turbidity in the influent even though particulate iron was still present in the influent. During the later months of operation, turbidity in the raw water increased dramatically on 2 sampling days. The cause for these increases is unknown, but one event occurred on a day in October when microbial numbers were also very high (59,000 CFU/100 mL). When only one well was used, the raw water had a turbidity  $<1$  NTU except for these 2 sampling days near the end of the study.

The turbidity exiting the sediment filter was sometimes significantly less ( $\alpha = 0.10$ , not significant at  $\alpha = 0.05$  and  $0.01$ ) than the influent concentration by an average of  $32 \pm 94\%$  (Figure 11). The ion exchange unit removed most of the remaining turbidity, so that the GAC unit with pretreatment received very little turbidity loading. The GAC without pretreatment removed turbidity from the water throughout the study. In a survey of water treatment plants that use GAC in the U.S., influent turbidities of 1.1 to 7.0 NTU were decreased to 0.1 to 0.5 NTU through the units (Graese et. al., 1987). Although turbidity was reduced through the GAC and ion exchange units, headloss was not observed. The ion exchange unit was backwashed every 2 weeks, so this result was expected, however, the GAC without pretreatment was not backwashed until late November. The data suggests that headloss development from retention of particulates in the GAC unit without pretreatment was negligible in this study. This may not hold true for GAC units that receive a higher turbidity loading.

The turbidity in the bubble plate and diffused bubble effluents was significantly greater ( $\alpha = 0.01$ ) than the influent concentration (Figure 12). The increase in turbidity in the aeration units was probably the result of iron oxidation and precipitate formation (see subsequent discussion of iron) during aeration (Figure 13).

## IRON

The total iron in the raw water was typically less than 0.6 mg/L and in most samples it was less than or equal to 0.3 mg/L except for 4 days over the course of the study. An average of 80% of this iron was soluble. The sediment filter removed an average of 24% of the total iron (Figure 14a) and usually negligible amounts of the soluble iron (Figure 14b), though some soluble iron removal was observed on a few occasions. It is hypothesized that the soluble iron was removed by the filter as a result of deposition of precipitate forms and/or sorption of complexed forms. The GAC unit without

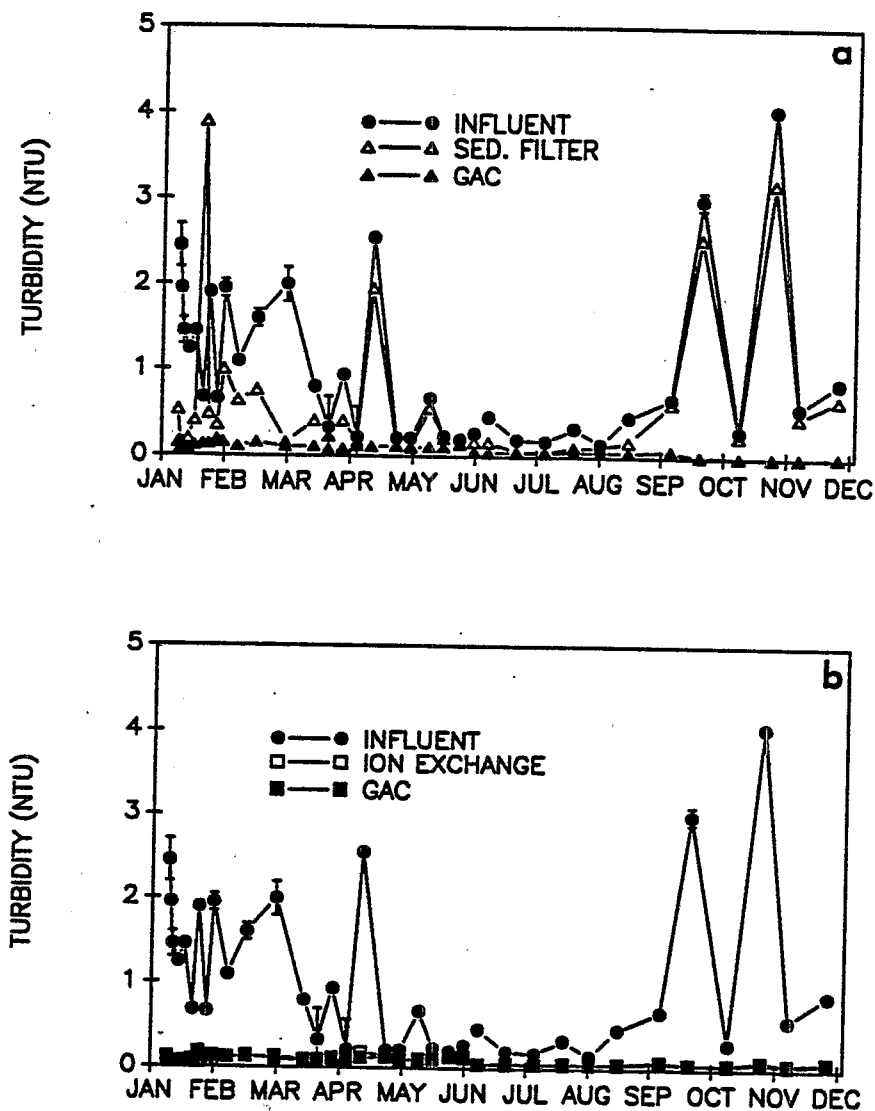


Figure 11. Turbidity for the GAC without pretreatment (a) and the GAC with pretreatment (b).

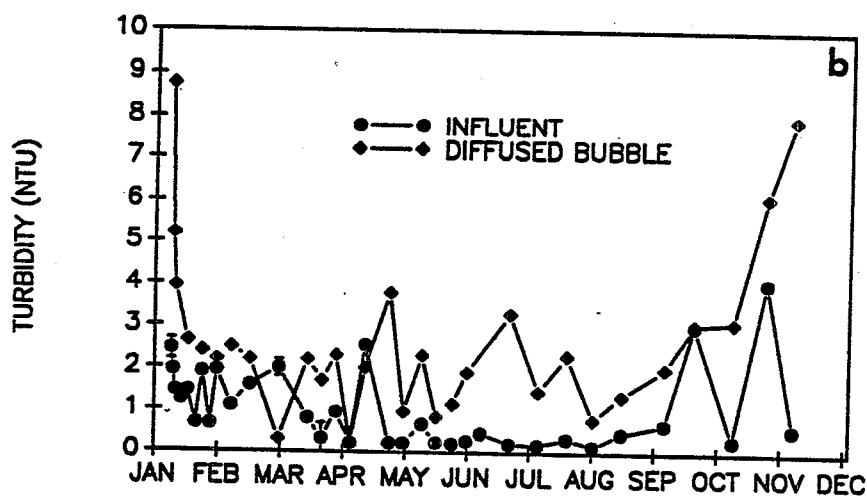
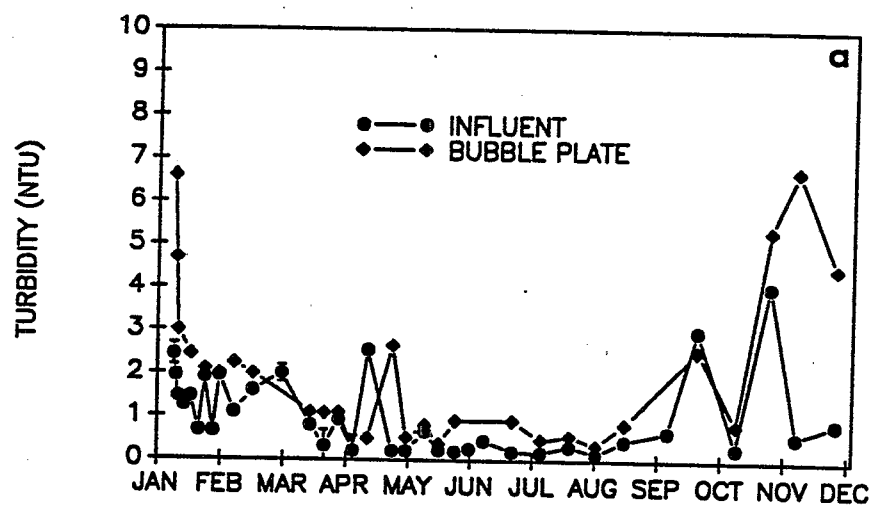


Figure 12. Turbidity for the bubble plate unit (a) and the diffused bubble unit (b).

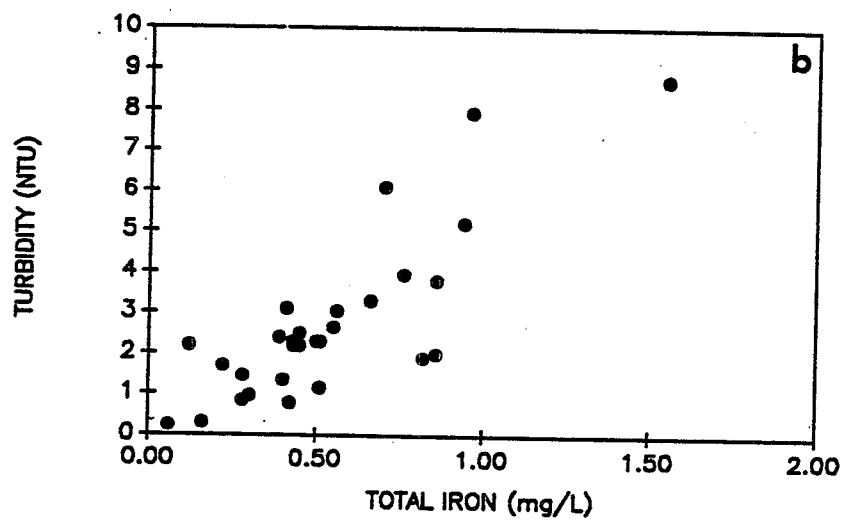
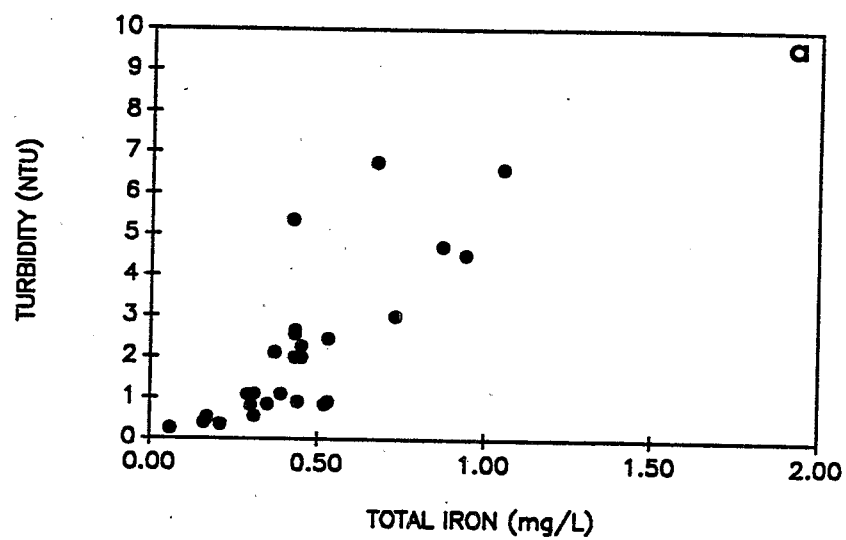


Figure 13. Turbidity as a function of total iron for the bubble plate unit (a) and diffused bubble unit (b).

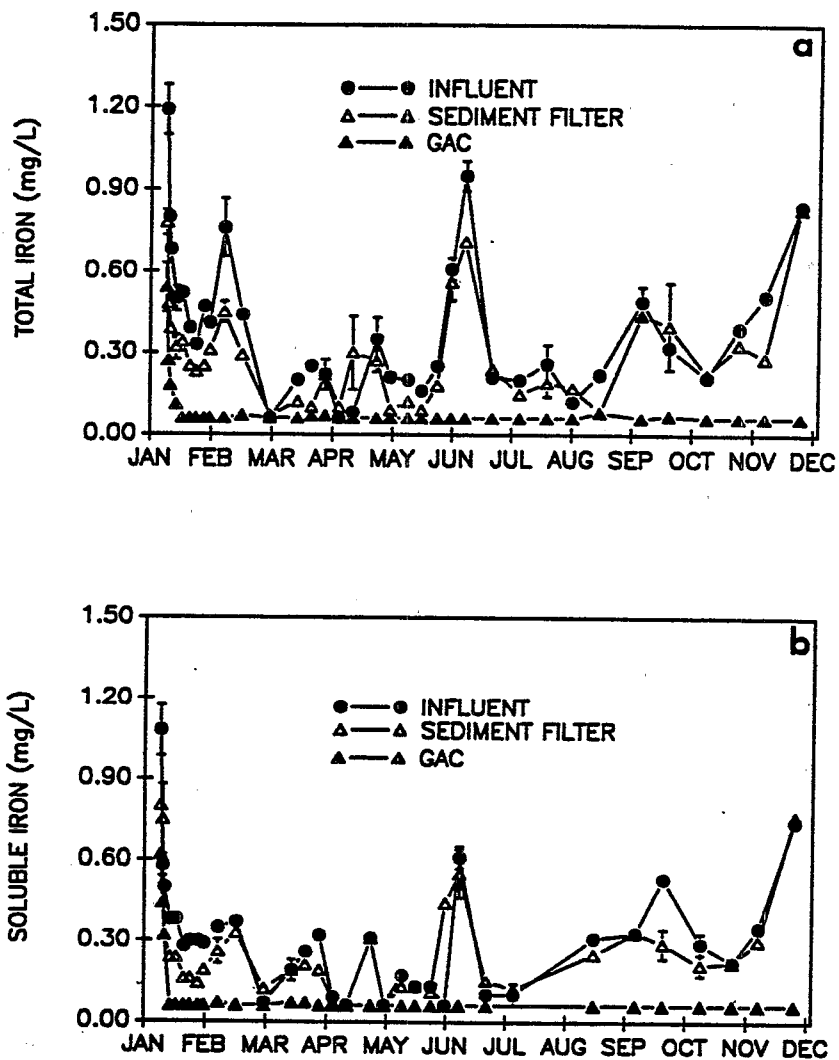


Figure 14. Total (a) and soluble iron (b) for the GAC without pretreatment. (detection limit = 0.06 mg/L).



pretreatment (Figure 14) removed all detectable iron (detection limit = 0.06 mg/L) from the water. A similar trend was observed in the small community radon removal studies for one of the GAC systems. (Kinner et al., 1990). The ion exchange unit removed all detectable iron from the water (Figure 15), hence no iron was applied to the downstream GAC.

The coring experiment data indicated that most of the iron removed by the GAC unit without pretreatment was retained in the top of bed (Table 7), with a marked decrease in concentration with depth. As expected, little iron was accumulated in the GAC with pretreatment. Visual inspection of the GAC bed in the unit without pretreatment during coring showed that a crust of orange-red precipitate was prevalent in the top 15.2 cm of the carbon. Below this depth, the GAC appeared unchanged. The carbon in the GAC with pretreatment had no visible fouling through the bed.

The effluent total iron concentrations for the bubble plate (Figure 16a) ( $0.43 \pm 0.24$  mg/L) and diffused bubble (Figure 17a) ( $0.53 \pm 0.30$  mg/L) units were somewhat higher than the influent ( $0.40 \pm 0.27$  mg/L). However, these differences were not usually statistically significant ( $\alpha = 0.10$  or  $0.05$ ). Conversely, the concentrations of soluble iron did significantly ( $\alpha = 0.01$ ) decrease through these units (Figures 16b and 17b). The data indicates that the aeration processes were causing iron to be oxidized and precipitated. The increase in total iron in the effluents probably resulted from the release of particulate iron accumulated in the units. Iron accumulations were observed in the water stored in both units between periods of operation. This was particularly true for the diffused bubble unit. Each unit is designed to aerate the water for a period of time (Bubble Plate = 1 min; Diffused Bubble = 10 min) after the influent flow stops. During this period, iron precipitates are probably formed in the units and subsequently released along with the effluent when a new cycle is started.

#### MANGANESE

The influent total manganese concentration in the raw water varied between 0.08 and 0.68 mg/L ( $\bar{X} = 0.36 \pm 0.12$  mg/L) during the study, 95% of which was soluble ( $\bar{X} = 0.35 \pm 0.11$  mg/L) (Figure 18). Manganese was not significantly ( $\alpha = 0.10$ ) changed in any of the units (Figures 18, 19, 20 and 21) during treatment except in the ion exchanger which lowered it below detection (0.02 mg/L). This was expected because the resin had a strong affinity for cations. In all other cases, manganese removal was not expected since manganese remains soluble below pH = 11 and oxidation/precipitation via aeration requires periods of >1 hr.

The coring data (Table 8) indicated that little manganese was retained in the GAC units. The concentration at the bottom of the GAC without pretreatment was the highest of the three depths sampled. It appeared that dissolved manganese entering the unit, was undergoing oxidation as it passed through the upper part of the GAC and being deposited as an insoluble complex

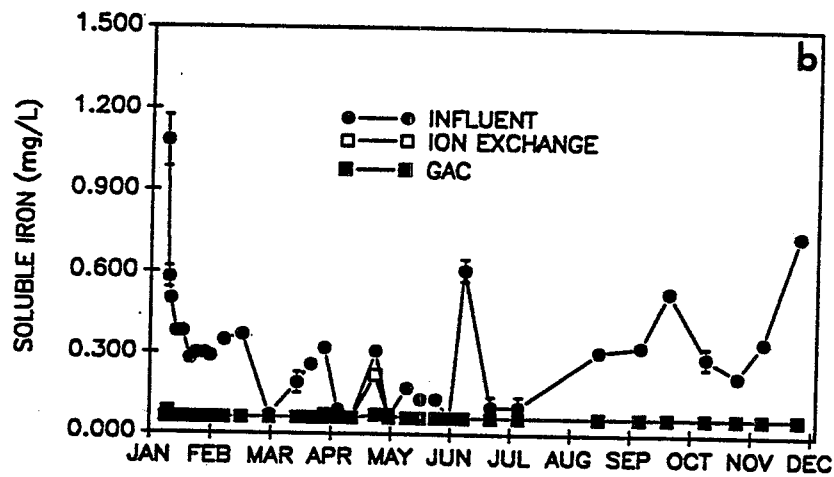
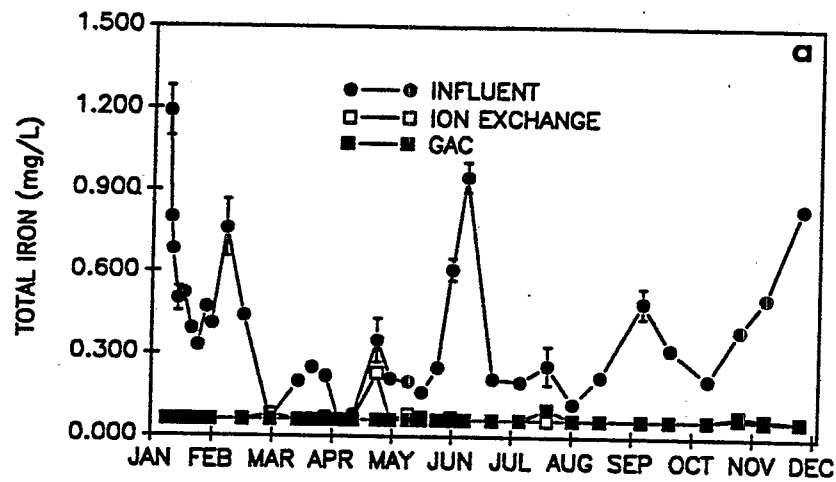


Figure 15. Total (a) and soluble iron (b) for the GAC with pretreatment. (detection limit = 0.06 mg/L).

TABLE 7. TOTAL IRON CORING DATA IN THE GAC UNITS

Location in Bed <sup>+</sup>	Total Iron (mg/kg <sup>*</sup> )	
	GAC without Pretreatment	GAC with Pretreatment
Top	13,520	425
Middle	1,110	ND <sup>#</sup>
Bottom	640	ND

<sup>\*</sup>All data reported on a dry weight basis obtained from the percent moisture analyses.

<sup>+</sup>In the GAC without pretreatment, coring depths were top, middle = 43 cm, bottom = 93 cm. In the GAC with pretreatment, coring depths were top, middle = 41 cm, bottom = 93 cm.

<sup>#</sup>Not detectable. Detection limit = 3 mg/kg.

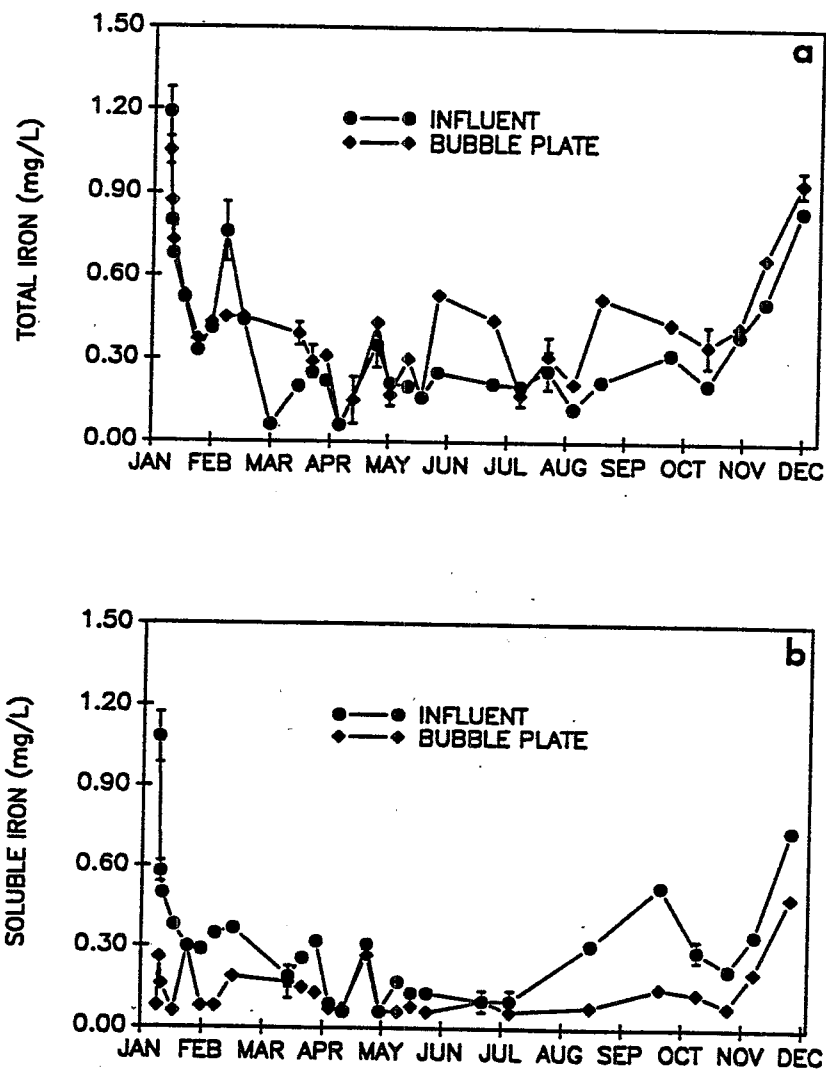


Figure 16. Total (a) and soluble iron (b) for the bubble plate unit. (detection limit = 0.06 mg/L).

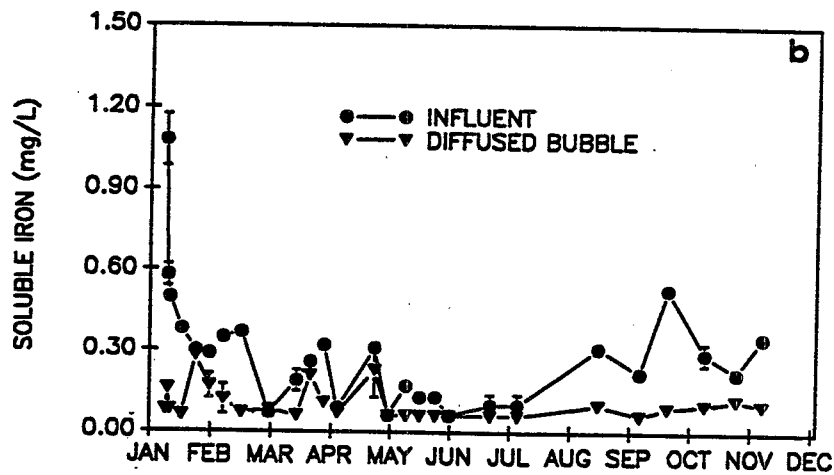
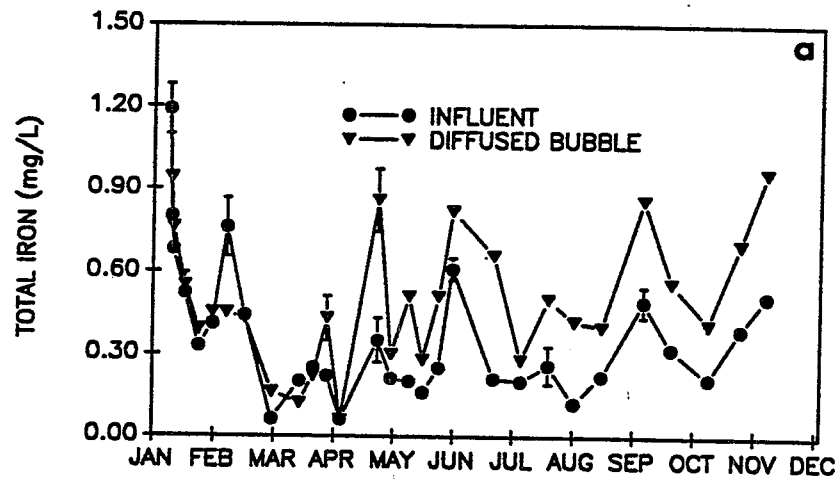


Figure 17. Total (a) and soluble iron (b) for the diffused bubble unit. (detection limit = 0.06 mg/L).

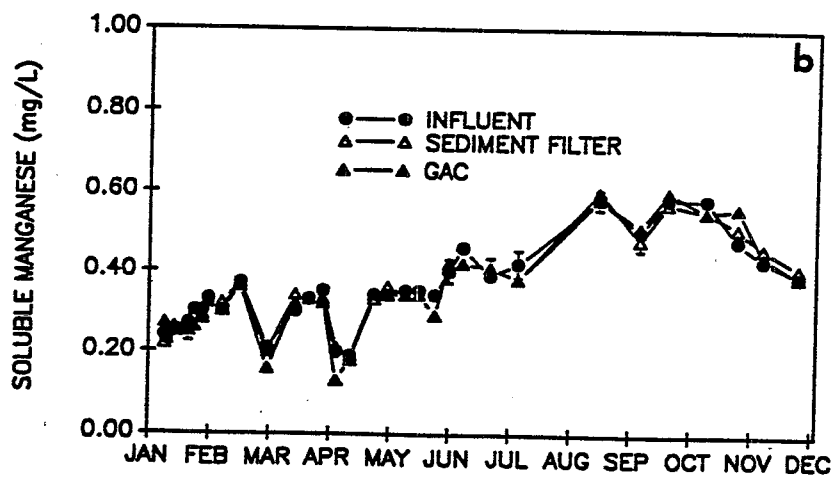
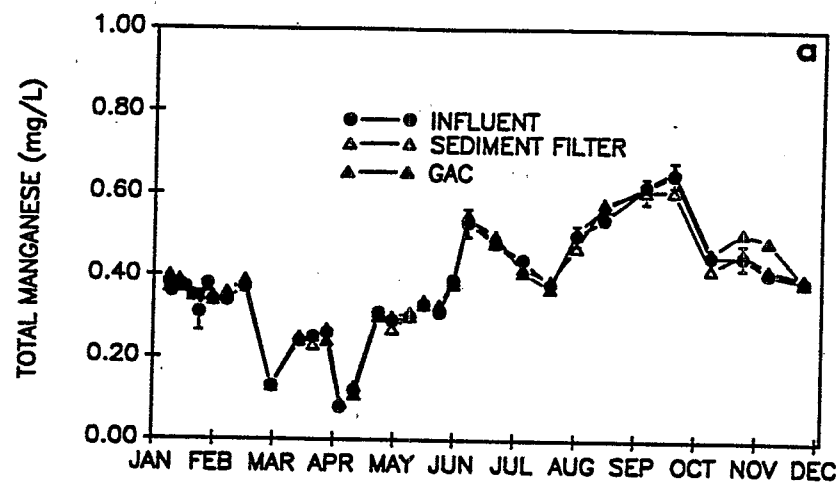


Figure 18. Total (a) and soluble manganese (b) for the GAC system without pretreatment. (detection limit = 0.02 mg/L).

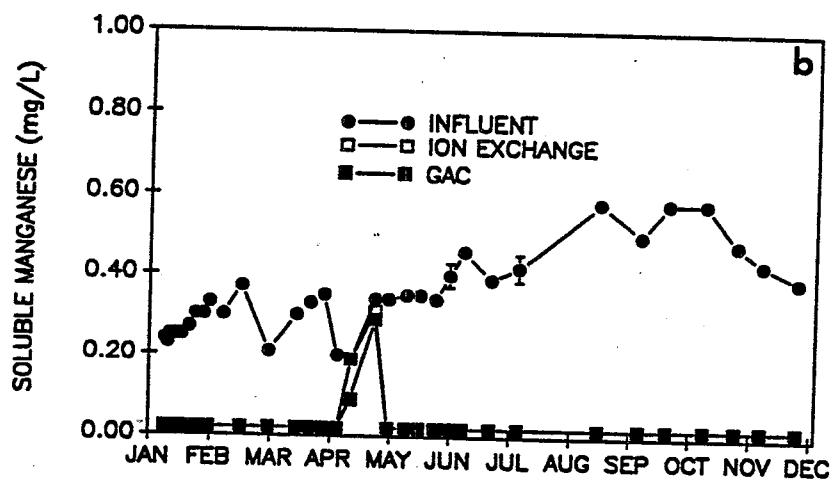
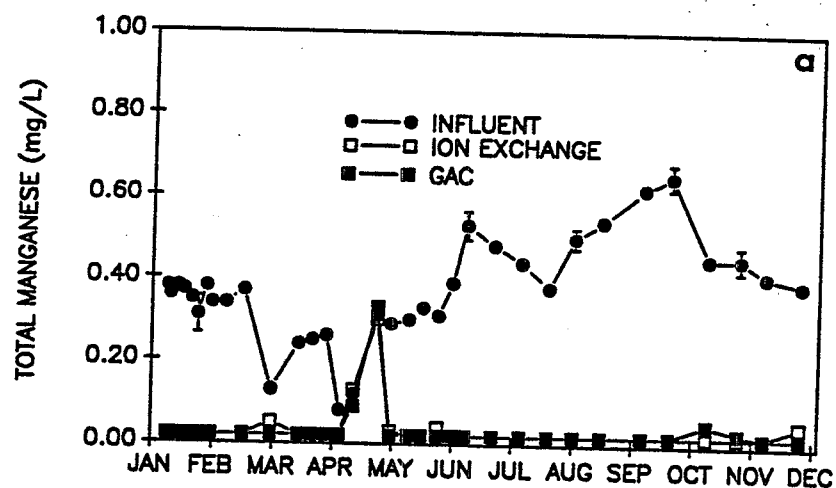


Figure 19. Total (a) and soluble manganese (b) for the GAC with pretreatment. (detection limit = 0.02 mg/L).

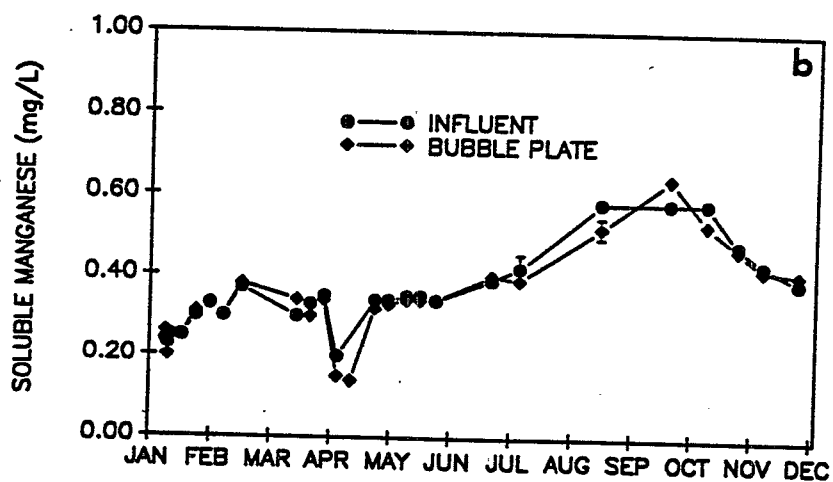
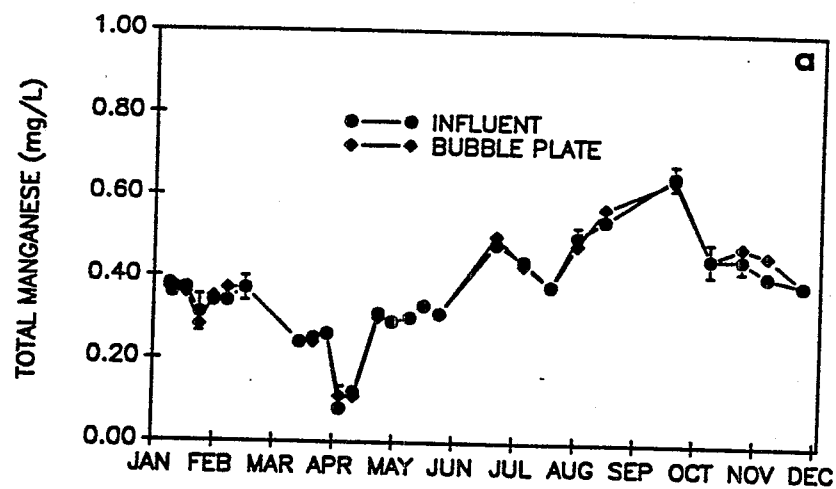


Figure 20. Total (a) and soluble manganese (b) for the bubble plate unit (detection limit = 0.02 mg/L).



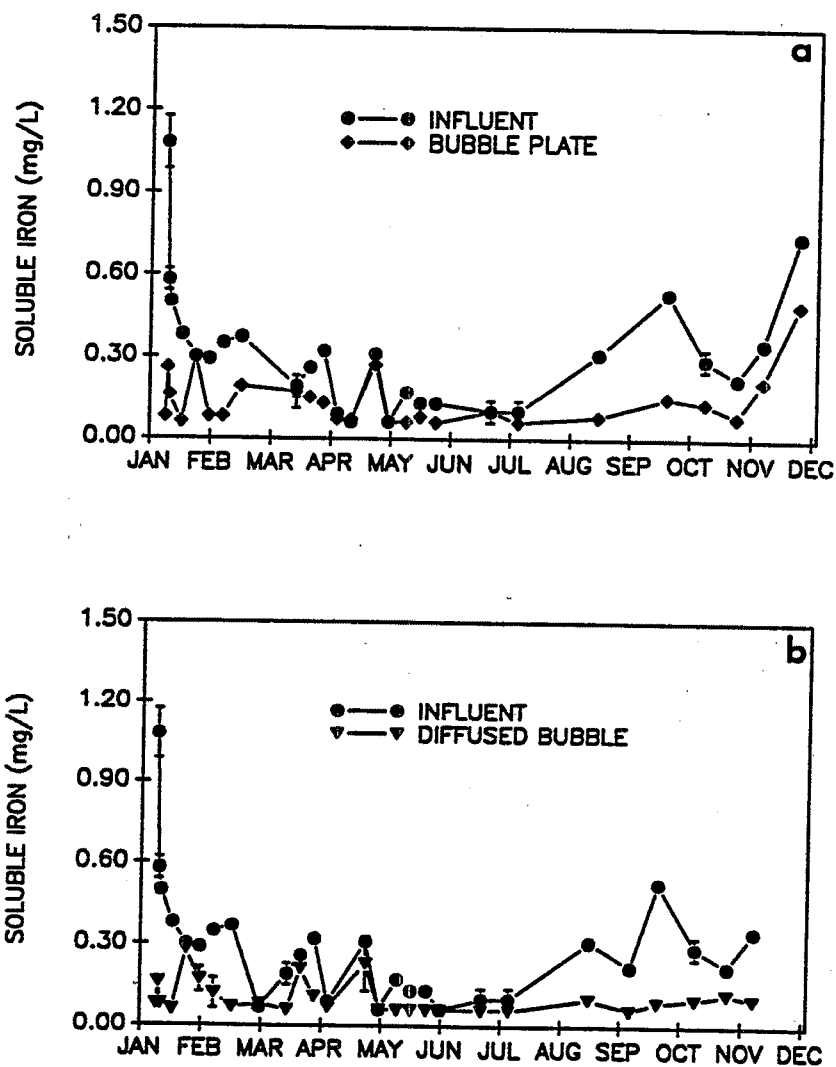


Figure 21. Total (a) and soluble manganese (b) for the diffused bubble unit. (detection limit = 0.02 mg/L).

TABLE 8. TOTAL MANGANESE CORING DATA IN THE GAC UNITS

Location in Bed <sup>+</sup>	Total Manganese (mg/kg <sup>*</sup> )	
	GAC without Pretreatment	GAC with Pretreatment
Top	1.45	ND <sup>**</sup>
Middle	0.30	ND
Bottom	6.35	ND

\* All data reported on a dry weight basis obtained from the percent moisture analyses.

<sup>+</sup> In the GAC without pretreatment, coring depths were top, middle = 43 cm, bottom = 93 cm. In the GAC with pretreatment, coring depths were top, middle = 41 cm, bottom = 93 cm.

<sup>\*\*</sup> Not detectable. Detection limit = 1 mg/kg.

in the bottom of the bed. A similar pattern was observed in the GAC units used in the small community radon removal study (Kinner et al., 1990).

#### MICROBIAL NUMBERS

During the period April through September, the influent raw water (Figure 22) at the site usually had no detectable bacterial contamination ( $<20,000$  CFU/100 mL) as assessed using R2A heterotrophic plate counting (N.B., microbial enumeration was not started until April). However, in late September and thereafter, the raw water contained bacteria in the range 20,000 to 59,000 CFU/100mL. This corresponded to the time when the raw water also had variable concentrations of alkalinity, calcium, iron and turbidity. It appears that during the late summer and fall, the ground water supplying the site was more influenced by changes in the water table and surface recharge. Such variability in water quality was observed in the previous long-term monitoring during the small community radon removal study (Kinner et al., 1990).

Neither the sediment filter (Figure 22a) nor the ion exchange unit (Figure 22b) significantly ( $\alpha = 0.10$ ) increased bacterial numbers. However, on certain days, the effluent from the ion exchange unit contained higher numbers than the raw water. Flemming (1987) noted that microbial growth in ion exchange units is common and can lead to their release into the finished water. In addition, the effluent from both GAC units (Figure 22) contained large numbers of bacteria (GAC without pretreatment =  $32,400 \pm 33,600$  CFU/100 mL; GAC with pretreatment =  $34,200 \pm 22,500$  CFU/100 mL), often greater than the concentration exiting the sediment filter and ion exchange unit, but overall not significantly different ( $\alpha = 0.10$ ) from the influent. These concentrations tended to fluctuate widely over time (range = 20,000 to 200,000 CFU/100 mL). A similar phenomenon was observed during the small community radon removal study (Kinner et al., 1990) and by other researchers (Wilcox et al., 1983). It has been well documented that GAC filters are capable of supporting microbial populations (Wilcox et al., 1983; Camper et al., 1985, 1986, 1987; Graese et al., 1987). As with the ion exchange unit, the GAC provides a good surface for attachment and concentrates the nutrients as well as the organic matter necessary for microbial maintenance and growth. The numbers observed in this study were within the ranges reported in the literature [0-30,000 (Wilcox et al., 1983) and 0-60,000 colonies/100 mL (Bourbigot, 1981)].

During the coring study in January 1990, samples of carbon collected from the two GAC units in January 1990 were analyzed for microbial numbers. The concentrations ranged from  $<1.80 \times 10^5$  to  $2.46 \times 10^5$  CFU/g. In the GAC without pretreatment, the highest concentration was at the top of the bed ( $2.46 \times 10^5$  CFU/g) and this decreased to  $<1.80 \times 10^5$  CFU/g in the samples taken at 43 and 93 cm depths within the bed. In the GAC with pretreatment, there was no clear profile within the bed [Top  $\leq 1.80 \times 10^5$  CFU/g, 41 cm =  $2.07 \times 10^5$  CFU/g, 97 cm  $\leq 1.80 \times 10^5$  CFU/g]. These data confirm that the GAC

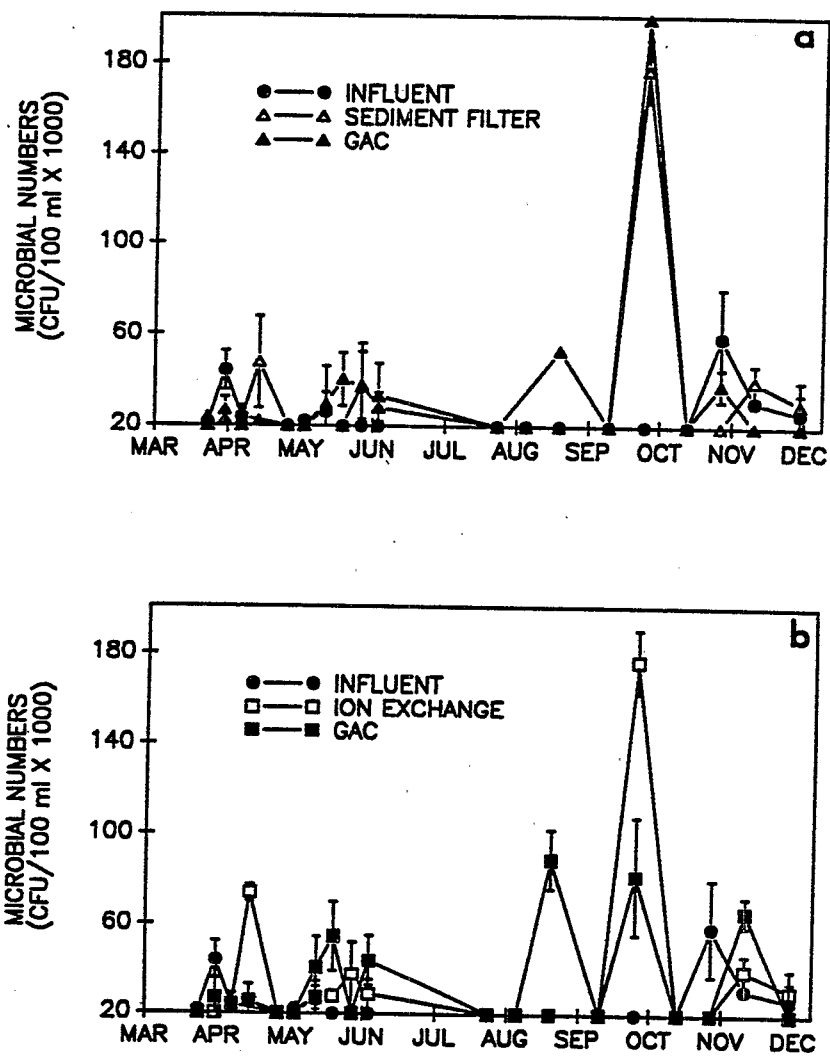


Figure 22. Microbial numbers for the GAC without pretreatment (a) and the GAC with pretreatment (b).

was fouled with microorganisms which could potentially be released into the water passing through the units.

The bacterial numbers exiting the aeration units (Figure 23) were sometimes greater than the influent concentrations. However, the average effluent bacterial concentrations were not significantly different than those in the influent ( $\alpha = 0.10$ ) nor those in the effluent from the GAC units ( $\alpha = 0.10$ ).

The data from all of the treatment systems indicated that bacterial contamination of the treated water will be a problem. The problem may be exacerbated by periodic increases in the microbial concentration in the raw water and by seasonal increases in temperature. Though regeneration and backwashing may lower bacterial numbers in the filter beds, they will not eliminate the contamination (Flemming, 1987). Consequently, all of the treatment units may need supplemental disinfection to insure that bacterial numbers in the finished water are reduced to acceptable levels.

#### NPDOC

In the small community radon removal study, the GAC's ability to remove radon from the water was less than predicted. One explanation proposed for this decreased efficiency was the accumulation of natural organic matter in the unit which could have changed the GAC's affinity to adsorb radon (Kinner et al., 1990). Hence, in the POE study, the GAC units were monitored for NPDOC.

The NPDOC concentration in the raw water ranged from 0.94 to 1.98 mg/L ( $\bar{X} = 1.30 \pm 0.28$  mg/L). This was similar to the average TOC ( $1.03 \pm 0.76$  mg/L) reported for Kansas groundwaters (Miller et al., 1990). NPDOC was effectively removed by both GAC units (Figure 24), but became increasingly more prevalent in the effluent over time. Breakthrough occurred in the period of July and August (Figure 25) and thereafter, the influent concentration was approximately equal to or less than the effluent. The data indicated that when the units were started after a quiescent period, there was a potential to have greater concentrations of NPDOC in the effluent. It is possible that NPDOC was desorbed from the GAC into the water flowing through the unit during these periods. Similar accumulation and breakthrough of NPDOC has been observed in pilot- and full-scale GAC water treatment systems studied by other researchers (Roberts and Summers, 1982; Weber et al., 1983).

#### RADIONUCLIDE REMOVAL

##### GAC

##### Radon --

The radon activity in the raw water at the Derry site ranged from 22,837 to 54,765 pCi/L, averaging  $35,620 \pm 6,727$  pCi/L (Figure 26). Variation in the influent during the first 6 months of the study was partially due to operating with water from 2 wells and to natural variation in the source. Variation in

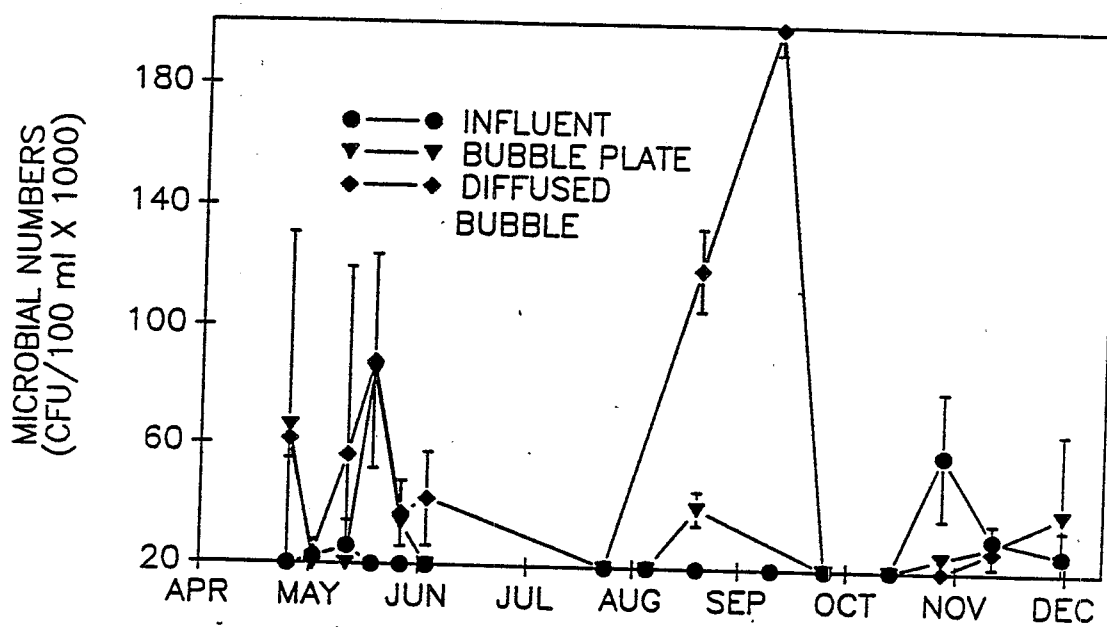


Figure 23. Microbial numbers for the aeration systems.

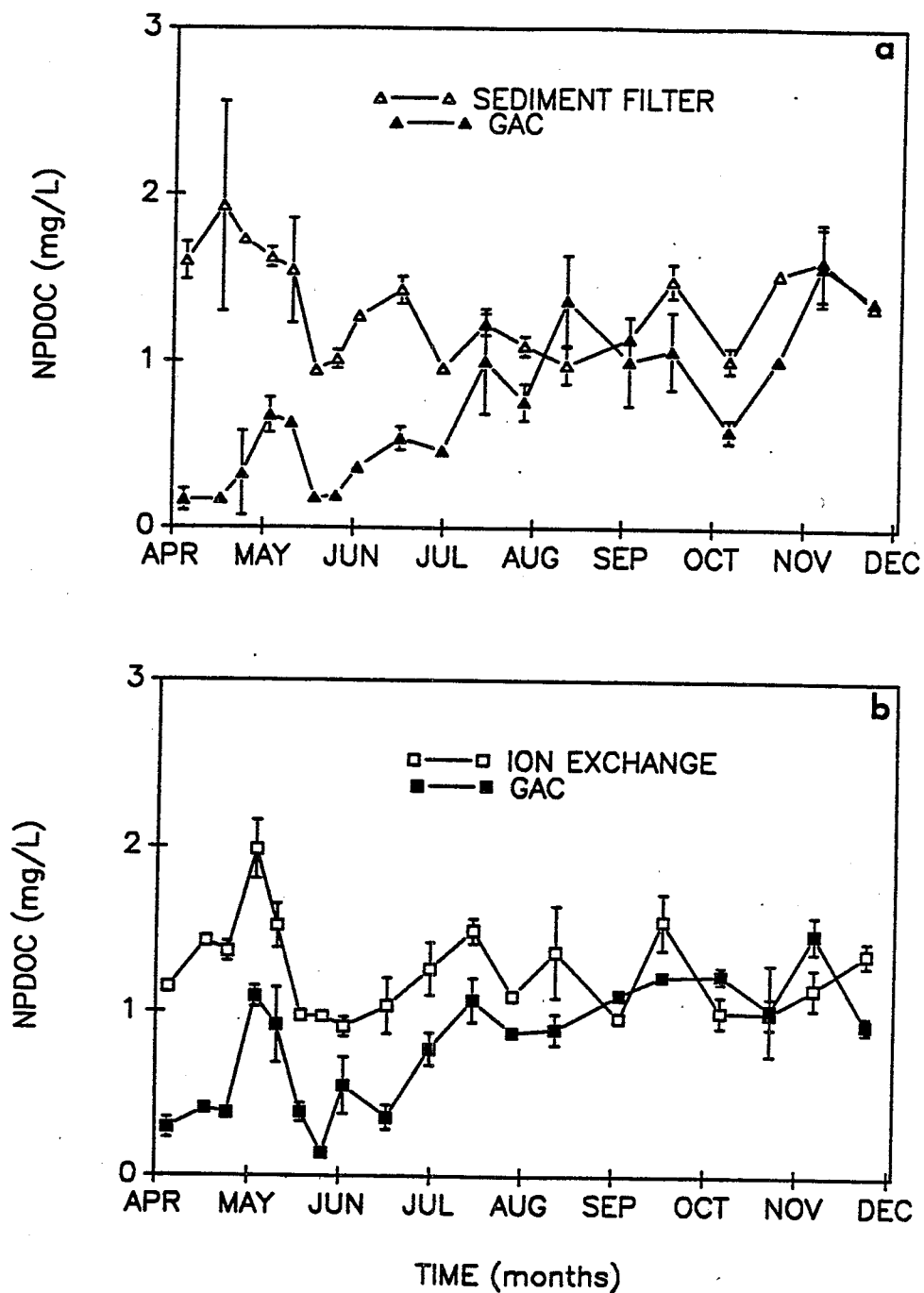


Figure 24. NPDOC for the GAC without pretreatment (a) and the GAC with pretreatment (b).

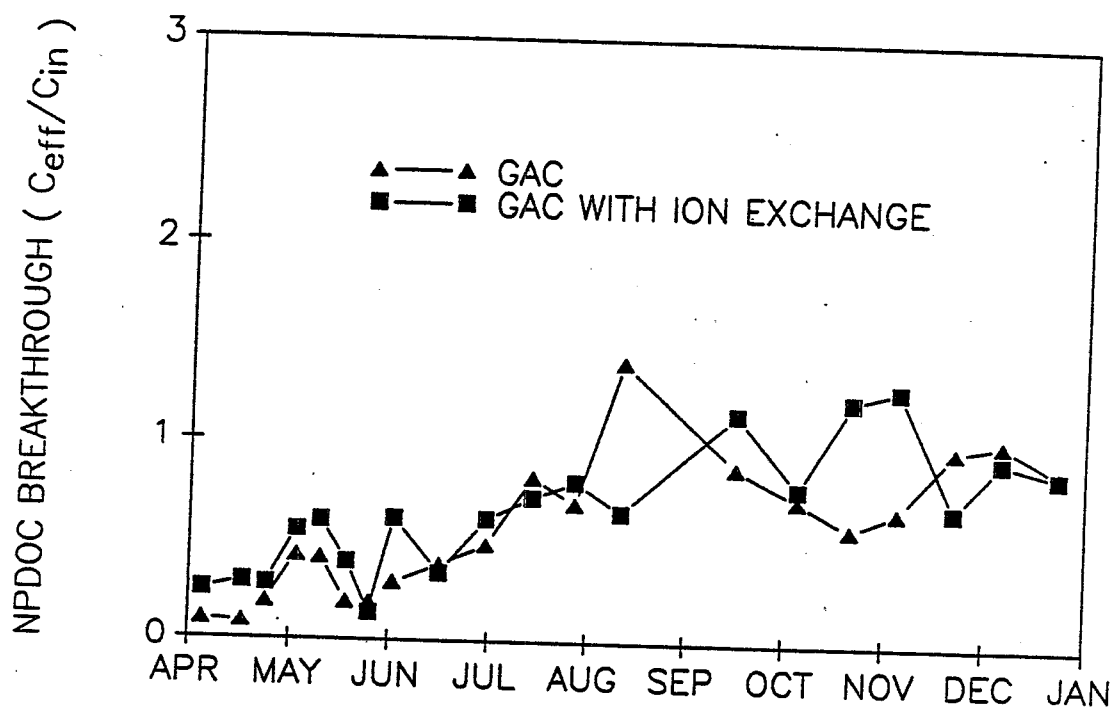


Figure 25. NPDOC breakthrough curve for the GAC units.



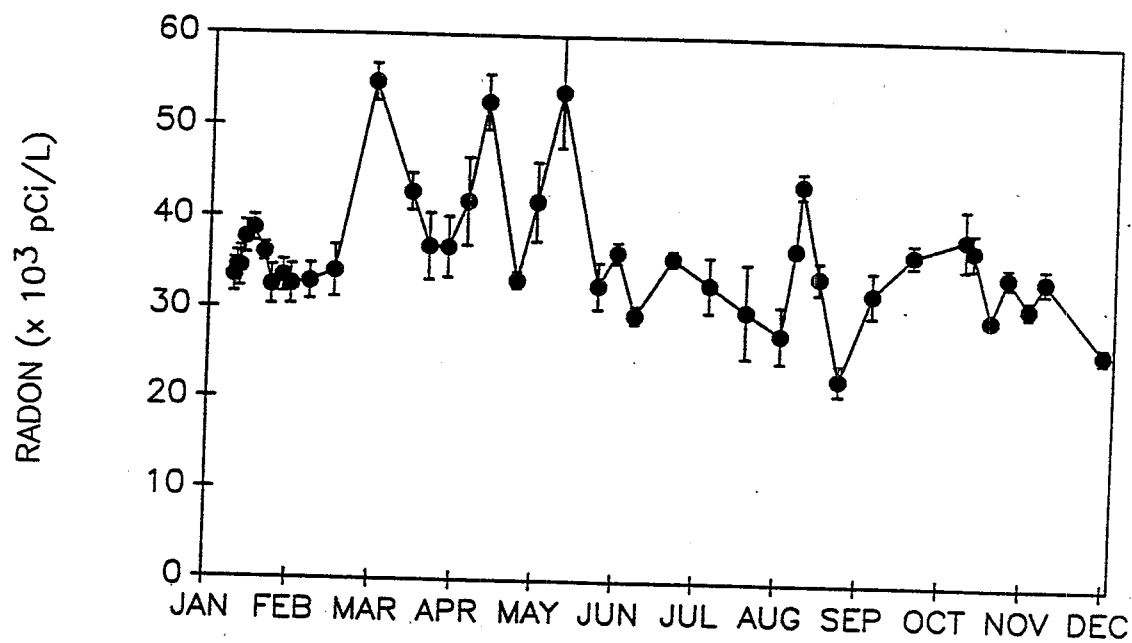


Figure 26. Influent radon activity for the POE treatment systems.

the latter half of the year was due to a single well and was similar to that observed in the small community radon removal study (Kinner et al., 1990). The sediment filter and ion exchange unit did not remove any detectable amount of radon from the water ( $\alpha = 0.05$ ). The effluent radon activity pattern from the two GAC systems (Figure 27a) was similar to that observed by Lowry and Lowry (1987) during the first 4 months of operation. The activity in the effluent was negligible for several days and then increased rapidly to an average of  $881 \pm 662$  pCi/L for the GAC without pretreatment and  $660 \pm 204$  pCi/L for the GAC with pretreatment where it remained until April. During the remaining 8 months of operation, the effluent activity from both GAC units generally increased, however, there was a large degree of variability in the data (Figure 27b). In some cases, there was a difference in the effluent quality of the two systems. These discrepancies were usually accounted for by the differences in the radon mass loading to the units (Figure 28) (GAC without pretreatment =  $299,219 \pm 85,942$  pCi/min; GAC with treatment =  $310,204 \pm 89,522$  pCi/min), mostly as a function of water flowrate.

Using a radon adsorption model presented in Lowry and Lowry (1987) with the influent and effluent radon activities and water flowrates from the POE GAC units, the steady state radon removal rate constant ( $K_{ss}$ ) was determined for comparative purposes. The mean  $K_{ss}$  values for the units were  $2.98 \pm 1.52$  hr<sup>-1</sup> (GAC without pretreatment) and  $3.29 \pm 1.29$  hr<sup>-1</sup> (GAC with pretreatment). These values compare favorably to the  $K_{ss}$  of  $3.02$  hr<sup>-1</sup> at 6-10°C obtained in other tests with this type of GAC (Lowry and Lowry, 1987). The range of  $K_{ss}$  values over the year was 1.17 to 7.39 hr<sup>-1</sup>. Differences in the quality of the water treated and the column hydraulics may have accounted for the differences in  $K_{ss}$  observed.

Most reports on GAC units used in POE applications have observed radon removals in the range 95 to >99% (Lowry and Lowry, 1987; Lowry et al., 1987; Lowry, 1988), whereas in our study the removal gradually deteriorated over time from 99.7 to 79% for the GAC without pretreatment and from 99.7 to 85% for the GAC with pretreatment. There are several factors which may explain such a deterioration in effluent quality. The most likely is a change in influent loading to the GAC. The mass loading of radon at the Derry site was within the range 130,000 to 653,888 pCi/min throughout the study, becoming somewhat less variable during the last 3 months of operation (Figure 28). However, it was during the latter period that the effluent quality deteriorated the most. The mass of radon applied was linearly correlated to the mass removed over the entire range of loadings (Figure 29) and a similar relationship was found for the cumulative mass relationships (Figure 30) for both units. When the data sets obtained for each unit were examined with respect to time, there were significant decreases ( $\alpha = 0.01$ ) in the slopes of the removal lines between the periods January through June as compared with July through December, especially for the GAC unit without pretreatment (Figure 31). However, there was no significant difference ( $\alpha = 0.10$ ) between the two units with respect to mass radon removal at any time. Further, a plot of the total radon activity adsorbed over time for each GAC unit showed their similarity, but appeared to be somewhat non-linear (Figure 32).

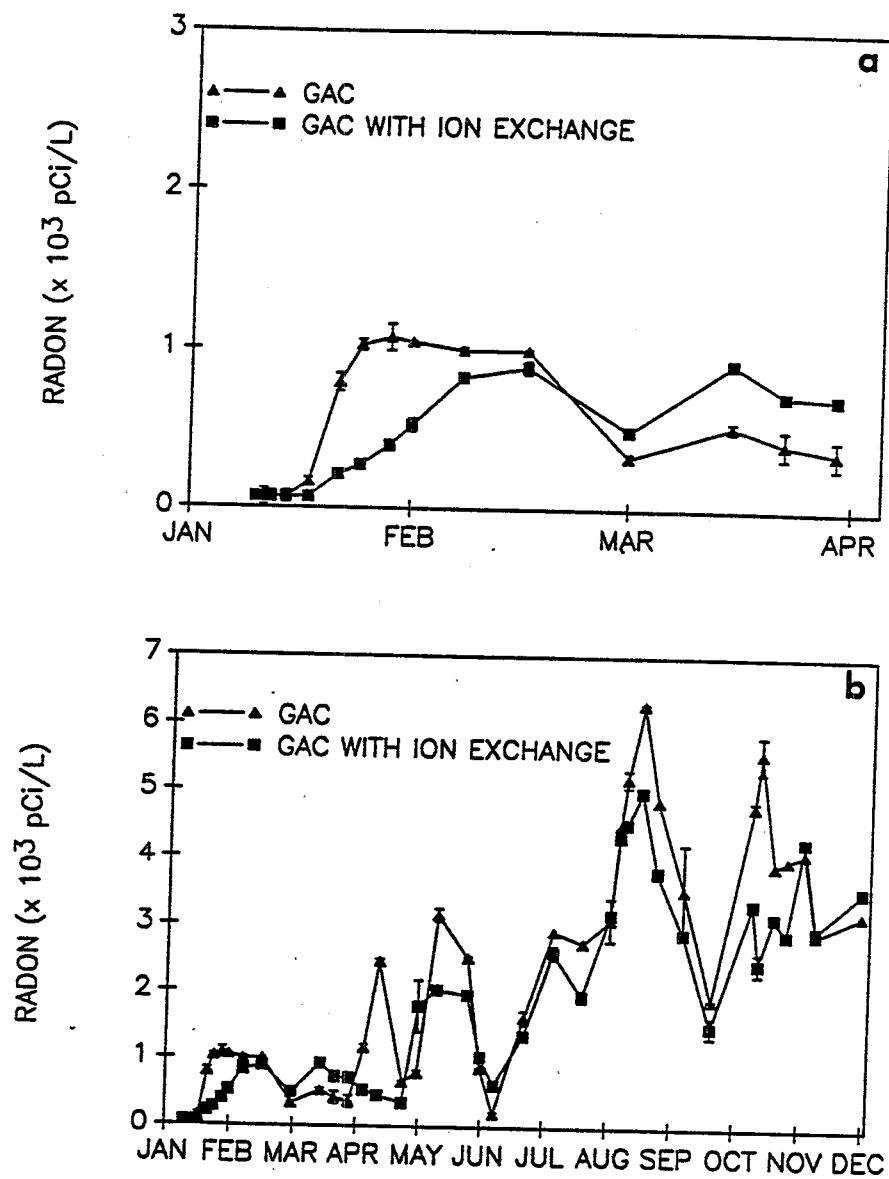


Figure 27. Effluent radon activities for the GAC systems for the first 4 months (a) and for the entire study (b). (note scale difference).

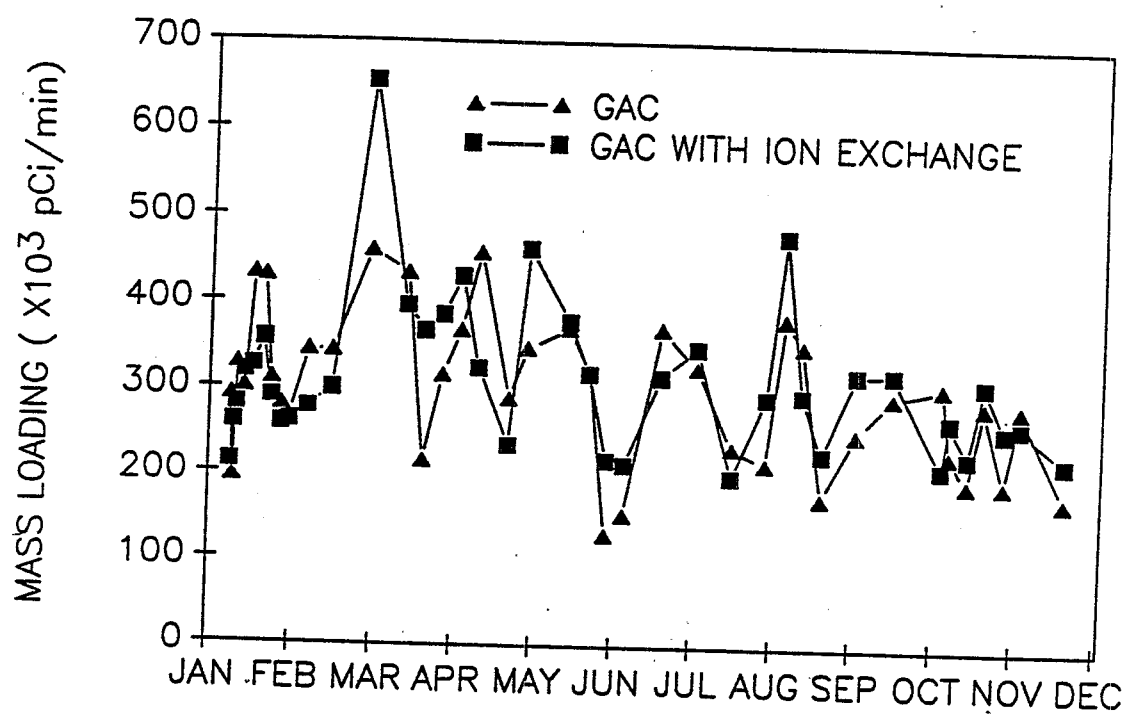


Figure 28. Radon mass loading rate to the GAC systems.

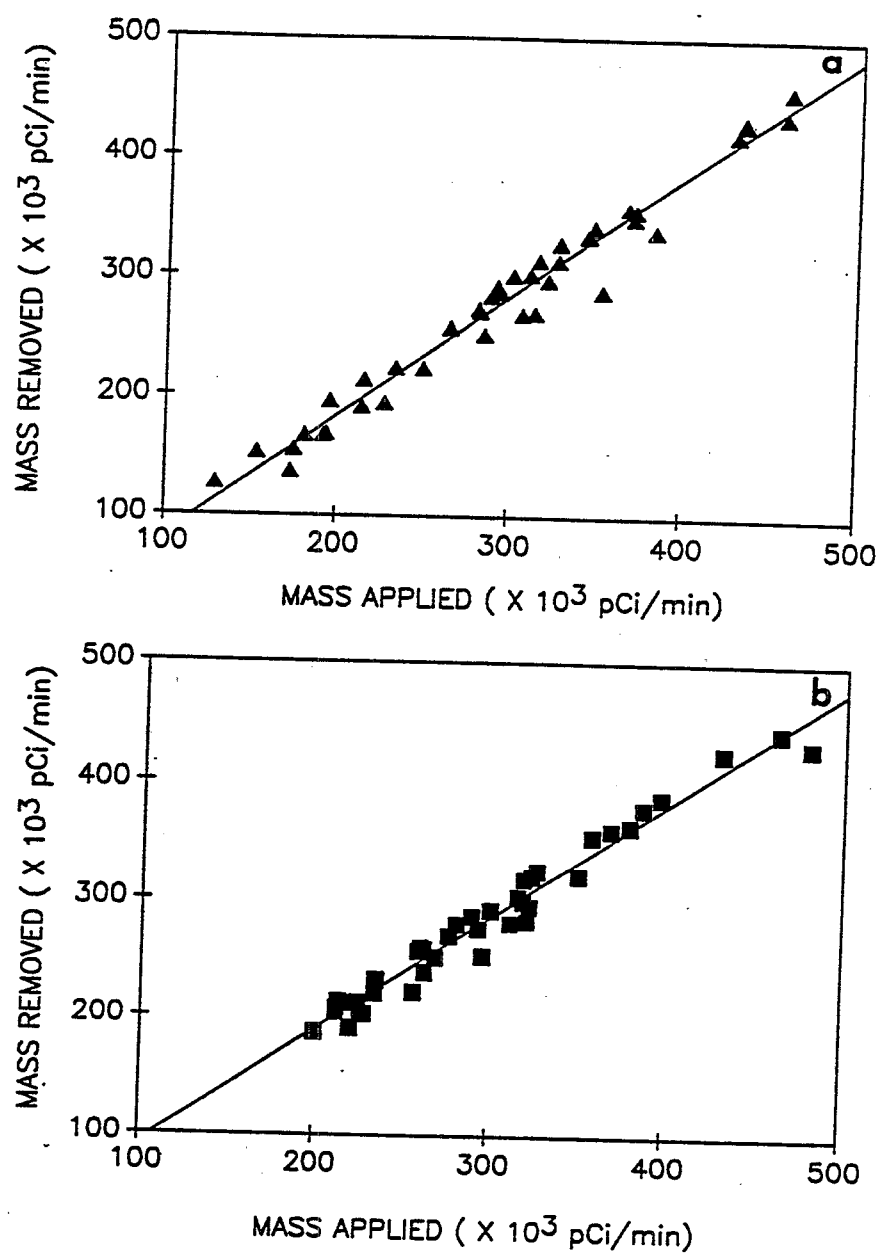


Figure 29. Radon mass removed as a function of mass applied for the GAC without pretreatment (a) and the GAC with pretreatment (b).

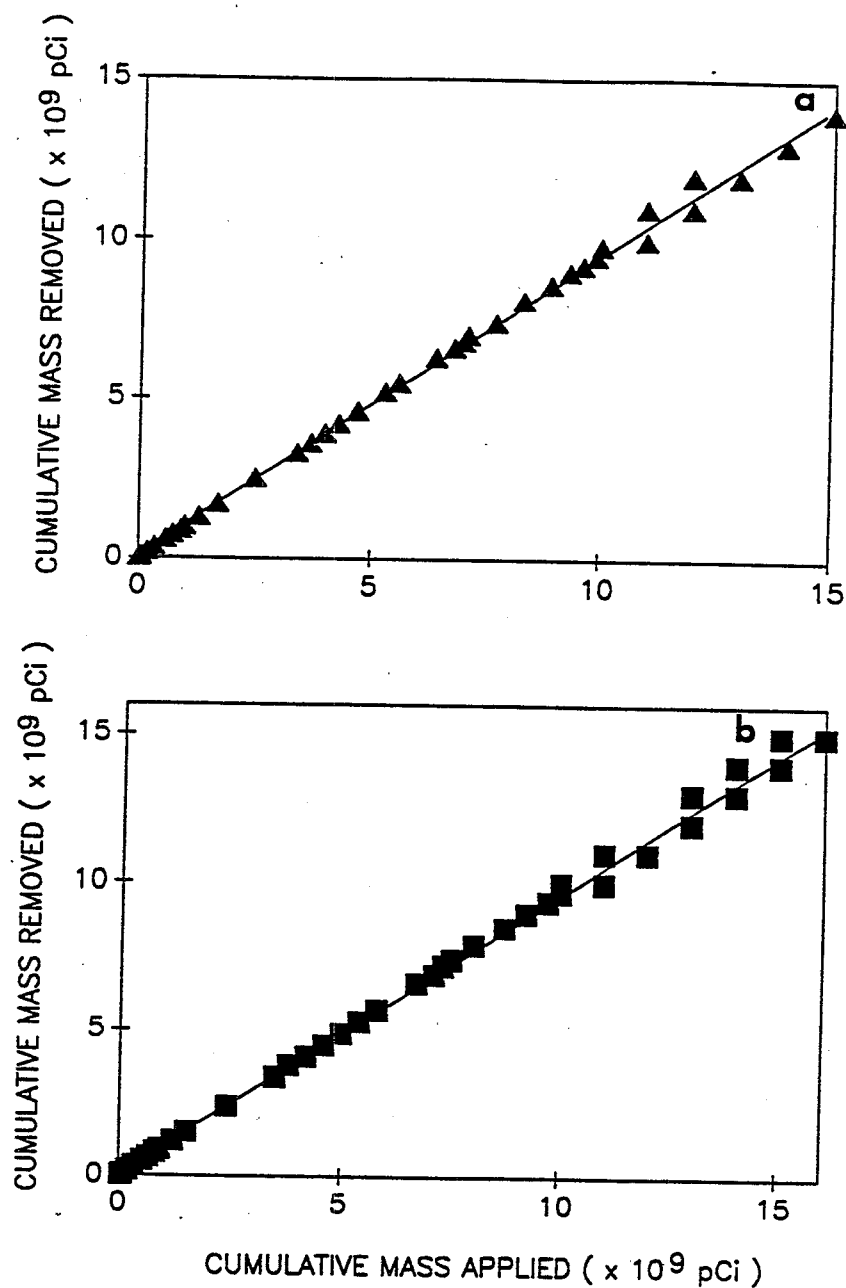


Figure 30. Cumulative radon mass removed as a function of cumulative mass applied for the GAC without pretreatment (a) and the GAC with pretreatment (b).

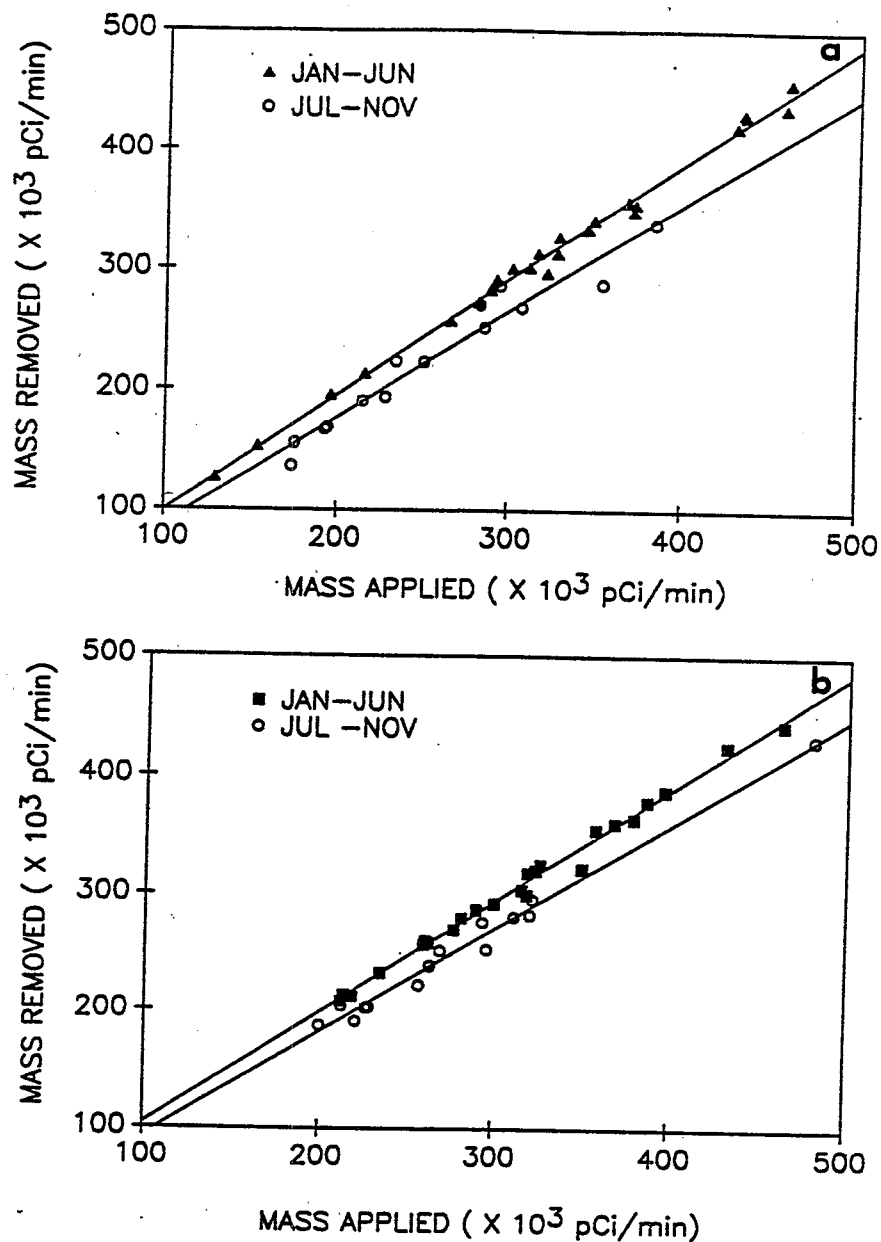


Figure 31. Radon mass removed as a function of mass applied for the first 6 months and the latter 6 months of the study for the GAC without pretreatment (a) and the GAC with pretreatment (b).

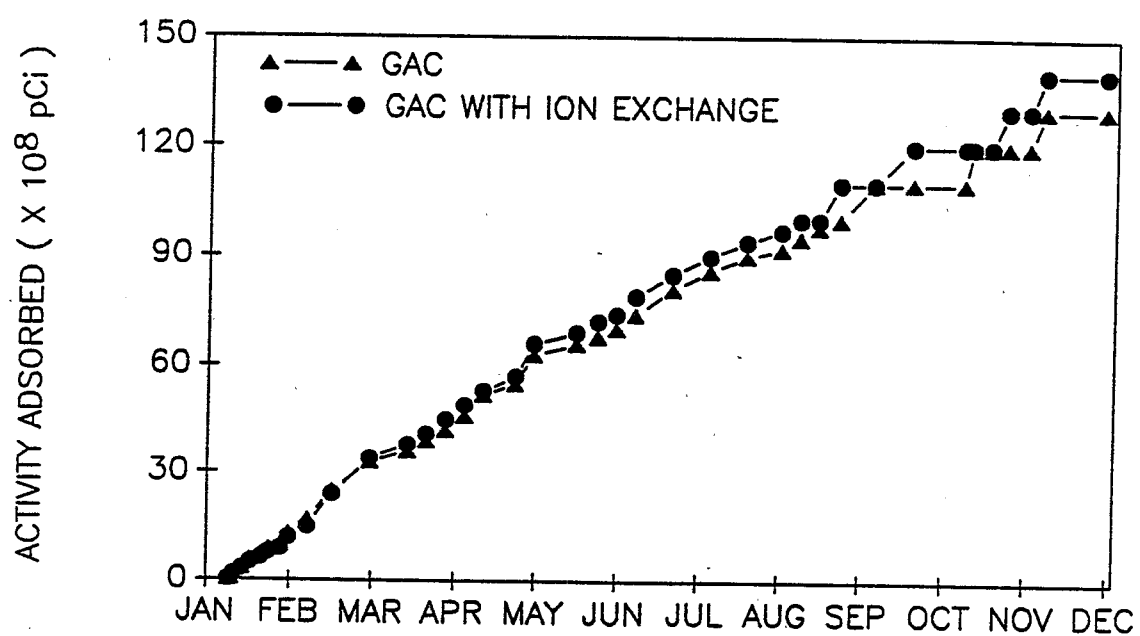


Figure 32. Total radon activity adsorbed over time for the GAC units.



The data suggest that the reduction in removal over time may be a function of the adsorptive capabilities of the GAC bed. Traditionally, it has been thought that GAC beds will not approach exhaustion with respect to radon for very long periods of time (Lowry and Brandow, 1985). This is expected because the mass of radon removed is very small even though the reduction in activity is high. Therefore, it was hypothesized that some other parameter in the raw water was sorbing to the GAC and reducing its capacity for radon. Initially, NPDOC was suspected because its breakthrough occurred in July/August when there was an increase in the radon in the effluent. Though there was an increase in the radon and NPDOC remaining in the effluent for both units (Figure 33), the correlation between them was not strong. Another possible candidate was iron, however, the GAC with pretreatment, whose radon removal decreased in a pattern similar to the GAC without pretreatment, did not receive any iron loading.

Unfortunately, in this study (unlike the small community radon project), we did not have sampling ports within the GAC bed. As a result, the radon removal profile could not be determined directly. However, gamma/beta emissions measurements were taken at the surface of the GAC tanks and these data show an interesting pattern (Figure 34). Initially in both units, the greatest gamma emissions occurred at the top of the bed. This was expected because the gamma emissions result from  $^{214}\text{Bi}$  and  $^{214}\text{Po}$ , which are both short-lived progeny of radon and high energy gamma emitters. The emissions at mid-depths (41-43 cm) were initially lower than those at the top of the bed because less radon was available to be removed at that depth. The bottom of the bed (93 cm) emitted much less gamma energy because there was little radon left in the water at that depth to be removed. Unlike small community GAC systems, POE units usually contain a large amount of excess carbon with respect to the amount required because of the relatively low cost of purchasing 0.028 to 0.084 m<sup>3</sup> of GAC. This excess GAC serves to dampen the effect of potential overloads to the system.

From April through the rest of the study, a greater amount of gamma emissions came from the mid-depth (43 cm) of the GAC without pretreatment than from the mid-depth (41 cm) of the GAC with pretreatment. This dose was also significantly ( $\alpha = 0.01$ ) higher ( $2.9 \pm 0.77$  mR/hr) than the emissions from the top of the bed ( $1.9 \pm 0.57$  mR/hr). Concurrently, there was slight increase in the gamma emissions from the bottom (93 cm) of this GAC bed over time.

Initially, in the GAC unit with pretreatment, the greatest gamma emissions were from the top of the bed. However, there was no significant ( $\alpha = 0.10$ ) difference between the gamma emissions from the top and middle (41 cm) of the bed from July until December. In this unit, there was a smaller increase in the gamma emissions from the bottom (93 cm) of the unit.

The gamma emissions data imply that the zone of radon removal in the units moved down the bed over time. This was especially true in the GAC unit without pretreatment. The effluent radon activity measured was not significantly different between the two GAC units. This lack of difference may have been caused by the excess amount of GAC present in both POE units.

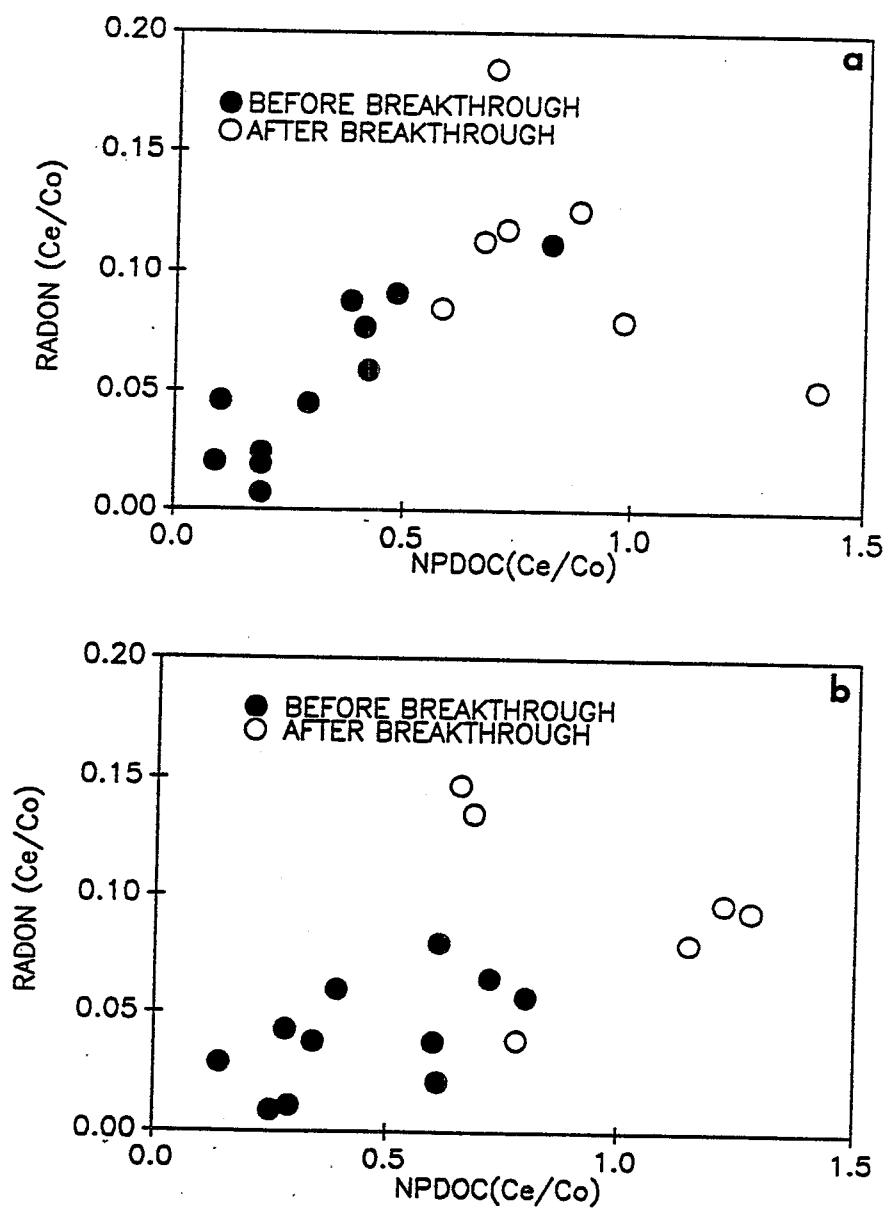


Figure 33. Radon breakthrough (Ce/Co) as a function of NPDOC breakthrough (Ce/Co) for the GAC without pretreatment (a) and the GAC with pretreatment (b).

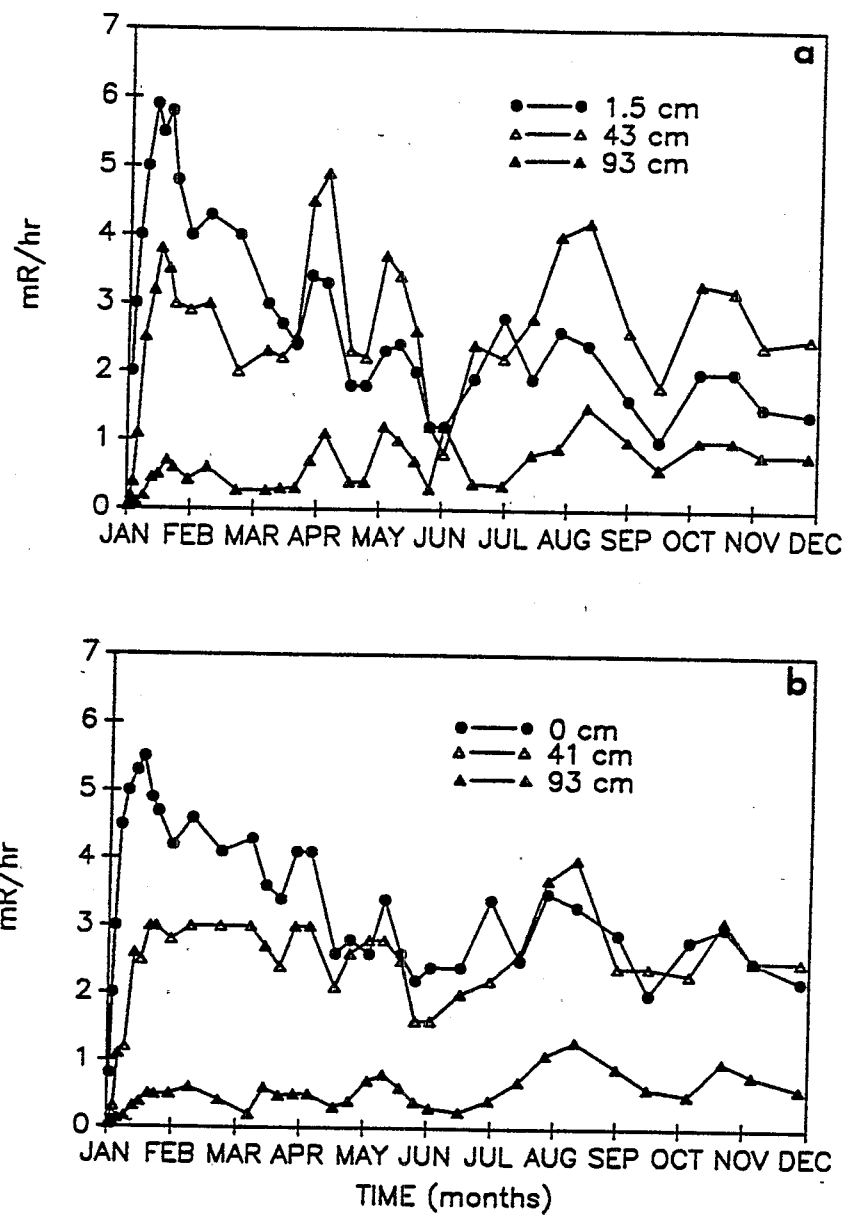


Figure 34. Gamma emissions measurements taken at the unit's surface for the GAC without pretreatment (a) and the GAC with pretreatment (b).

The units were cored in January 1990 to determine the activity of lead-210 retained in the GAC. Rubin and Mercer (1981) reported that GAC adsorption capacities for non-radioactive lead range from  $6.2 \times 10^4$  to  $1.9 \times 10^6$   $\mu\text{g/kg}$  at pH 6.5 and from  $2.1 \times 10^6$  to  $1.8 \times 10^8$   $\mu\text{g/kg}$  at pH 8.0 (based on Langmuir adsorption isotherms). Comparison of these data to the lead-210 coring results (Table 9) indicated that the GAC's capacity for lead-210 was at least  $10^7$  to  $10^{11}$  times higher than the actual and predicted lead-210 loading. This supports the hypothesis that lead-210 should be retained by the GAC unit. This hypothesis was confirmed by the comparison of the predicted lead-210 adsorbed based on radon mass removal to the actual lead-210 found from the coring data (Table 9).

The lead-210 profiles in both beds suggested that the greatest radon retention occurred at the top of each bed. However, while the radon loadings to the two GAC beds were not significantly different ( $\alpha = 0.10$ ), the lead-210 accumulations on the top of the GAC bed without pretreatment were significantly less ( $\alpha = 0.05$ ) than those in the GAC with pretreatment. At the mid-depth, the two beds were not significantly different ( $\alpha = 0.10$ ) in lead-210 adsorbed. While at the bottom, the lead-210 was significantly greater ( $\alpha = 0.10$ ) in the GAC without pretreatment.

The lead-210 retention data and the gamma emissions data from the survey meter indicated that radon removal was occurring deeper within the bed for the GAC without pretreatment. The iron data from the coring experiment of the GAC without pretreatment showed that there was significant accumulation ( $\alpha = 0.01$ ) of iron precipitates in the top of the bed as compared to the GAC with pretreatment. Visually, the greatest red-orange precipitate accumulations were observed in the top 15 cm of the bed. It is possible that the iron precipitation in the GAC impeded radon sorption by fouling the GAC surface or causing short-circuiting (channeling) of water in the top of the bed. As a result, the radon removal front appeared to be moving further down the bed in the GAC without pretreatment, so that the volume of excess carbon available for polishing was reduced.

Loading Rate Experiments -- The radon removal over the course of a day was monitored twice (February and August) when the flowrate was  $\sim 7.6$  L/min and the total daily throughput was  $\sim 1,022$  L/day (i.e., a normal cycle). The effluent activity was not significantly different ( $\alpha = 0.10$ ) over the course of the day. Similar results were obtained during the small community radon removal study. The data indicated that both GAC units were able to dampen short term changes in radon activity (Figure 35).

A series of 3 loading experiments were conducted one week apart during 2 months (August and October). When the flowrate remained between 7.7 to 8.9 L/min, but the total throughput was increased to 1,900-2,100 L/day, there was a significant ( $\alpha = 0.01$ ) decrease in the ratio of radon mass removal to mass loading over time during the second run (Figure 36). The other two loading conditions tested had flowrates in the range 20.4 to 22.6 L/min, and total throughputs of 1,264 to 1,400 L/day, and 1,904 to 2,139 L/day, respectively. In both of these cases, although the effluent radon activities were similar,

TABLE 9. COMPARISON OF PREDICTED LEAD-210\* REMOVAL IN THE GAC UNITS TO THE CORING DATA

Location in Bed <sup>‡</sup>	Lead-210 Measured (ug/kg GAC) <sup>+</sup>	
	GAC without Pretreatment	GAC with Pretreatment
Top	0.00457 (370 x 10 <sup>3</sup> )**	0.00549 (445 x 10 <sup>3</sup> )
Middle	0.00323 (262 x 10 <sup>3</sup> )	0.0033 (265 x 10 <sup>3</sup> )
Bottom	0.000946 (73 x 10 <sup>3</sup> )	0.00080 (65 x 10 <sup>3</sup> )
$\bar{X}$ in Bed	0.0029 (235 x 10 <sup>3</sup> )	0.0030 (246 x 10 <sup>3</sup> )
Predicted in Bed*	0.00457 (371 x 10 <sup>3</sup> )	0.00494 (402 x 10 <sup>3</sup> )

\* See Appendix D for methods of calculation.

<sup>+</sup> All data reported on a dry weight basis obtained from the percent moisture analyses.

<sup>‡</sup> In the GAC without pretreatment, coring depths were top, middle = 43 cm, bottom = 93 cm. In the GAC with pretreatment, coring depths were top, middle = 41 cm, bottom = 93 cm.

\*\* Values in parentheses are the lead-210 activity measured in pCi/kg dry weight.

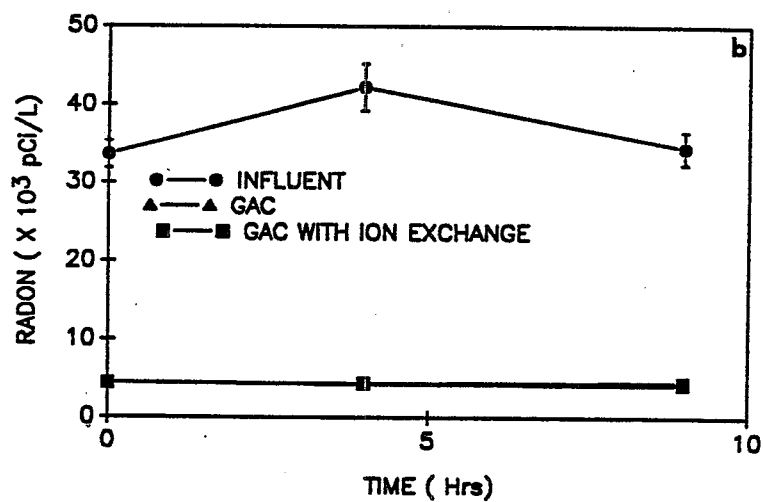
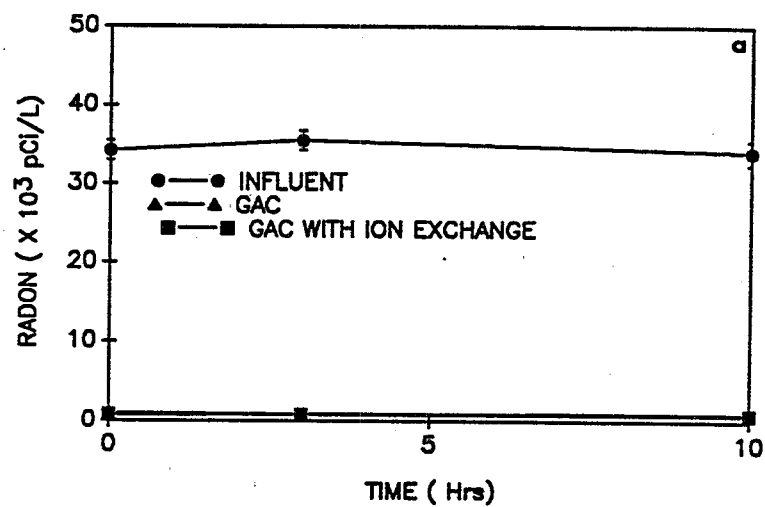


Figure 35. Radon activities for the diurnal study for the GAC systems. (February = a; August = b).

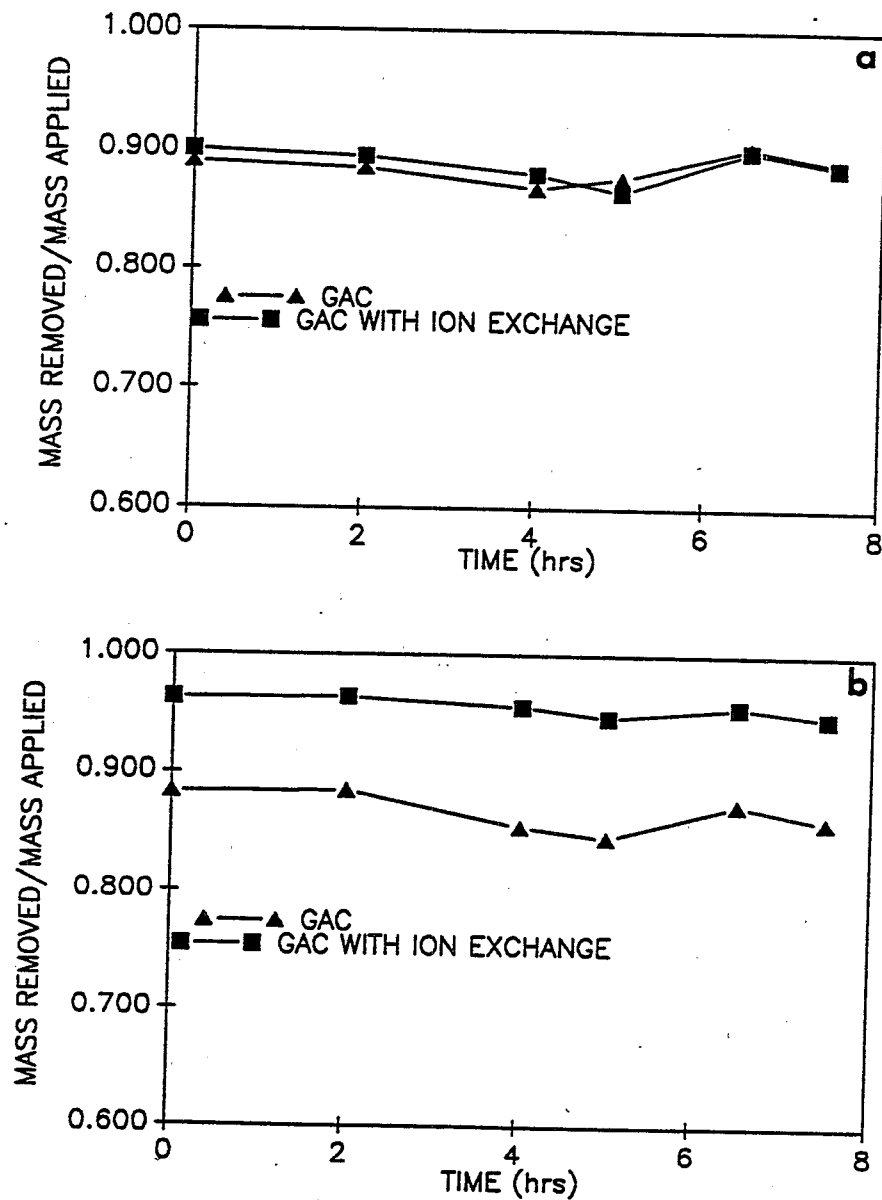


Figure 36. Ratio of radon mass removed: mass applied for the high loading rate study for the GAC systems. (August = a; October = b). (flowrate ~ 7.6 L/min; throughput = 1,900 L/day).

the mass removal of radon was significantly less ( $\alpha = 0.01$ ) in the GAC without pretreatment (Figures 37-38). On the days following these events, the effluent radon activity from the GAC units was sometimes higher than on the previous sampling event (Figure 39) indicating that the increased loading may have adversely affected radon removal for a period of time after loading returned to normal. Figure 40 also showed that the mass removal during the 20 L/min flowrate was significantly ( $\alpha = 0.01$ ) lower for both GAC units than that achieved at the normal 7.6 L/min flow. These data, in conjunction with the gamma emissions and lead-210 data indicated the GAC may become saturated with respect to radon even though it is in very low concentrations ( $10^{-10}$  to  $10^{-11}$  mg/L). It appears that over time, the ability of the GAC to dampen mass loading variations may be reduced. Therefore, in POE applications, effluent radon activities greater than the proposed MCL of 200-2,000 pCi/L may result. Furthermore, it appears that a GAC system's loss of resilience may be exacerbated by accumulation of iron in the top of the bed.

Backwashing Experiment -- Each bed was backwashed with raw water for 12 to 14 min, as recommended by the manufacturer, until GAC appeared in the backwash water. Backwashing did not change the radon removal observed in either GAC unit (Figure 41) nor did it affect gamma profiles or any of the other water quality parameters except for a small increase within the few hours of operation. This initial decrease in water quality, after restarting a backwashed filter, is typically observed in granular media systems (Amirtharajah, 1988). Interestingly, the backwash water did not contain a continuous release of iron precipitate as was observed in the small community GAC backwash water. Only small bursts of iron precipitate were released.

#### Gamma Exposure Dose/Shielding Event --

The maximum survey meter readings (mR/hr), taken at the surface of the tank, were divided by the influent radon activities (pCi/L) to determine the correlation between dose and influent radon activity. The average values (10,658 and 10,581 mR/hr/pCi/L GAC without and with pretreatment, respectively) were in the range reported by Lowry and Brandow (1985) and Lowry (1988). However, as noted in the small community radon study (Kinner et al., 1990) and by Rydell et al. (1989), these relationships are affected by the geometry, the type of detector used and the proximity to the source.

Survey meter measurements were also taken 1.5 m from the GAC tanks (Figure 42). Though the two GAC systems were in separate sections of the Derry pumphouse, there may have been some interferences. It was also difficult to get readings completely around the GAC tanks because of the restricted space in the building. The data collected were within 80% to 100% of the values obtained using the Carbdose 2.0 program developed by Keene and Rydell (1989) when an average influent radon activity of 35,620 pCi/L, water flowrate of 1,122 L/day, and 90% removal were used. The Carbdose 2.0 model also predicts the distance at which the probable exposure dose is less than 0.058 mR/hr based on the National Council on Radiation Protection residential guideline value (Keene and Rydell, 1989). The model predicted that for the Derry water supply the required distance was 189.5 cm.



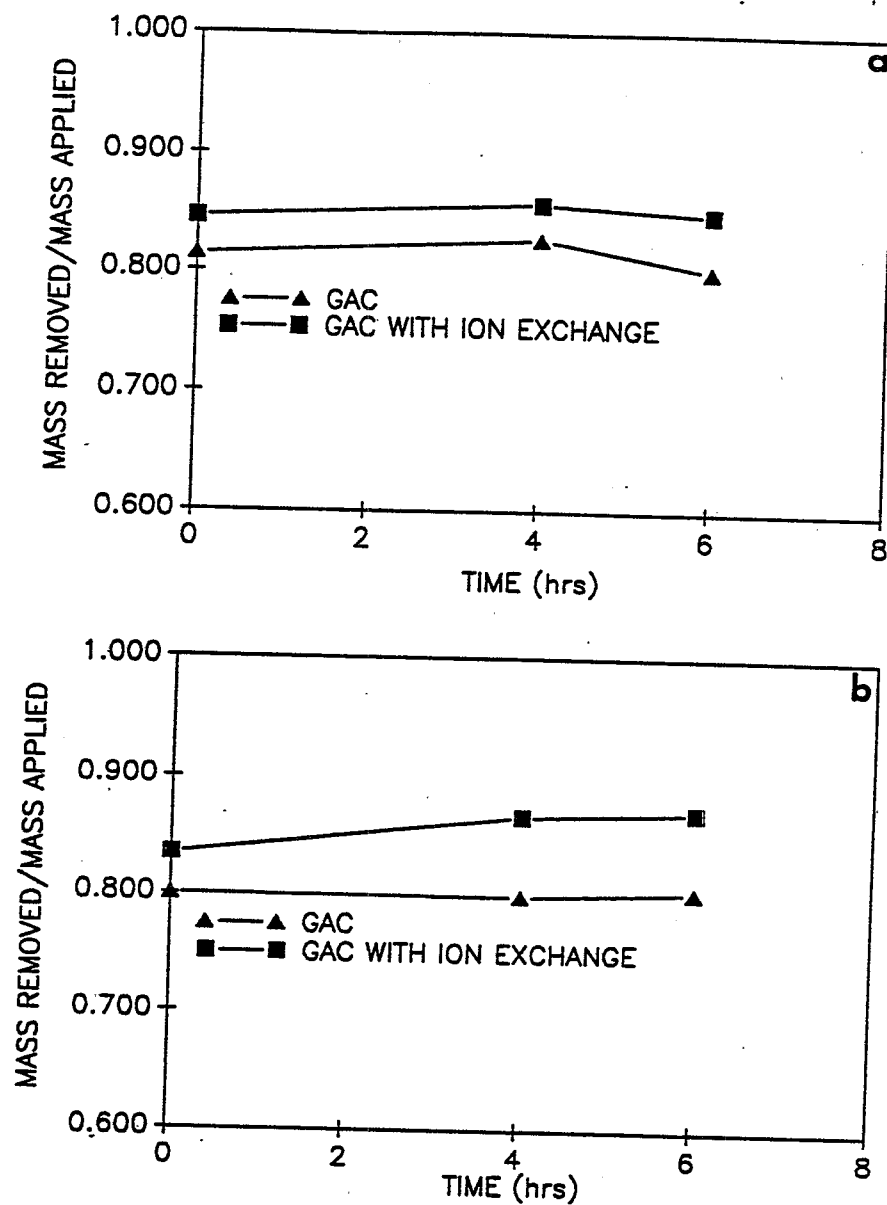


Figure 37. Ratio of radon mass removed: mass applied for the high loading rate study for the GAC systems. (August = a; October = b). (flowrate ~ 20 L/min; throughput = 1,050 L/day).

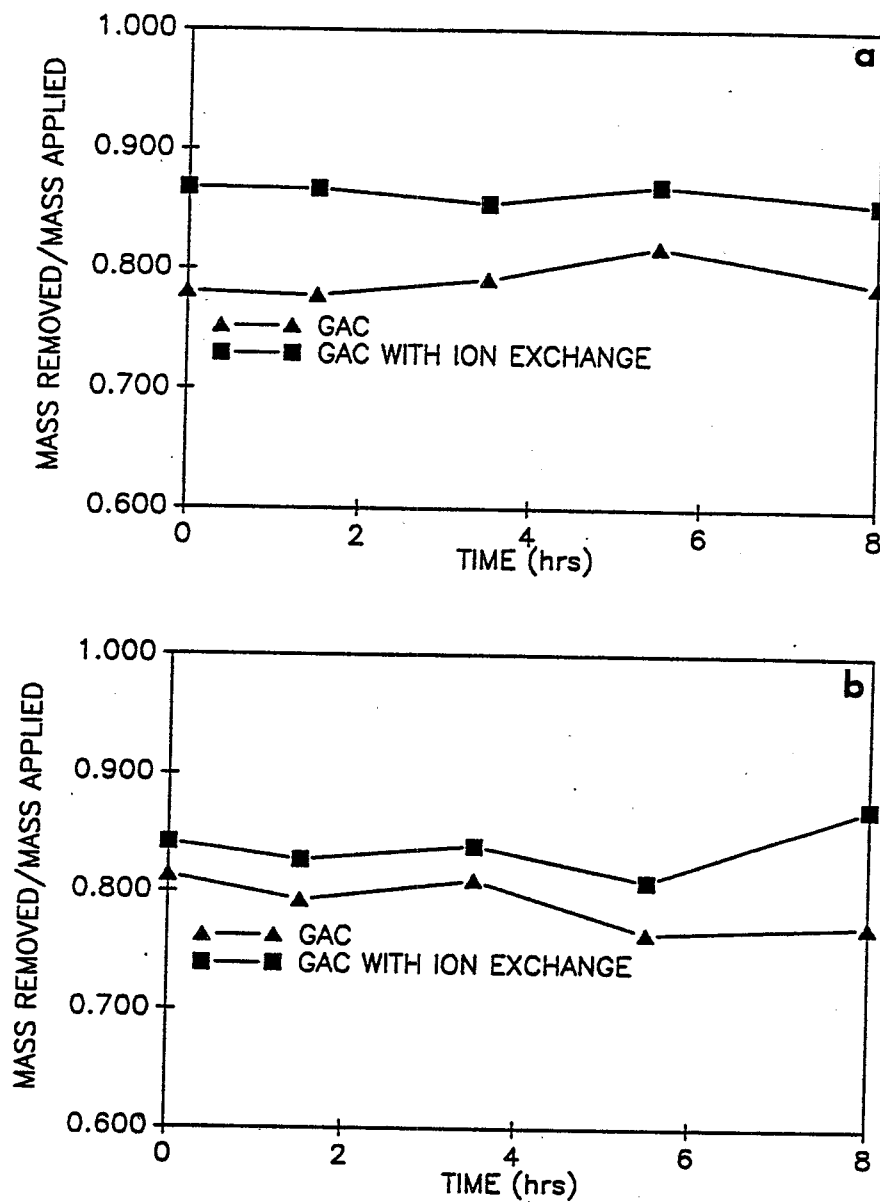


Figure 38. Ratio of radon mass removed: mass applied for the high loading rate study for the GAC systems. (August = a; October = b). (flowrate ~ 20 L/min; throughput = 1,900 L/day).

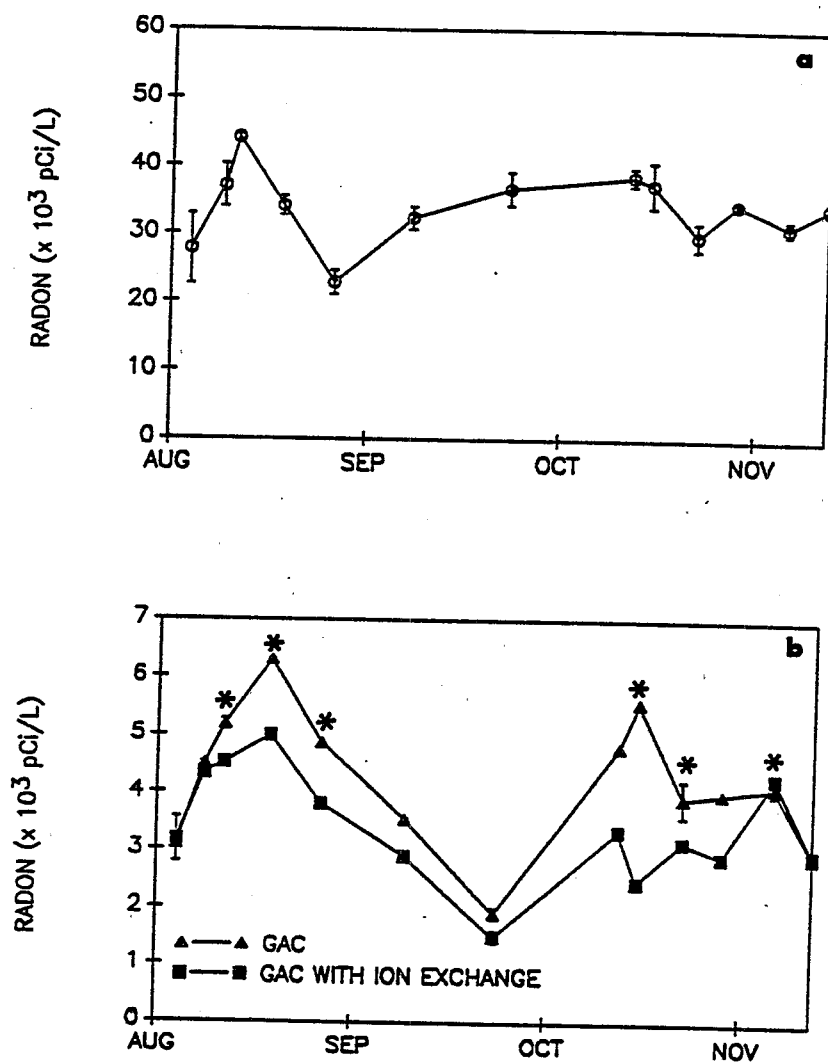


Figure 39. Radon activities for the influent (a) and effluent (b) of the GAC systems for the period of August through November. (note scale difference). (\* denotes sampling event following high loading experiment).

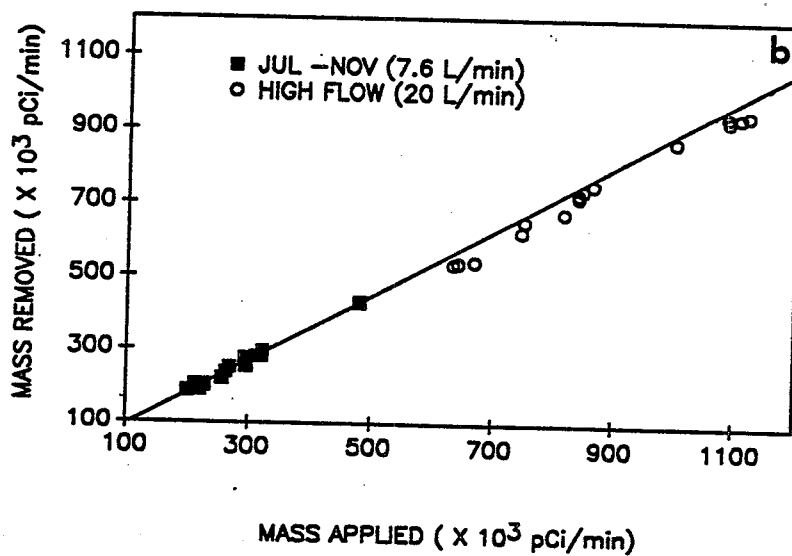
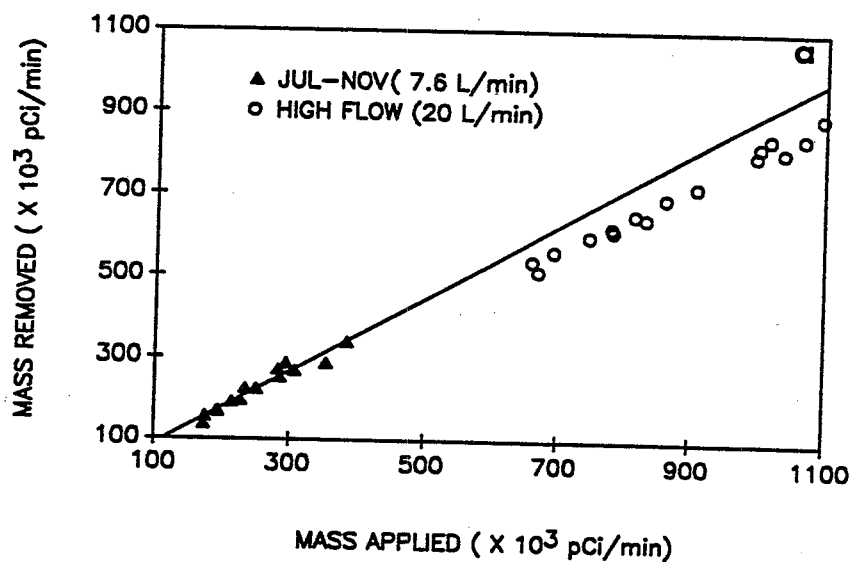


Figure 40. Radon mass removal as a function of the mass applied for the high loading rate conditions and for the normal conditions for the GAC without pretreatment (a) and the GAC with pretreatment (b).

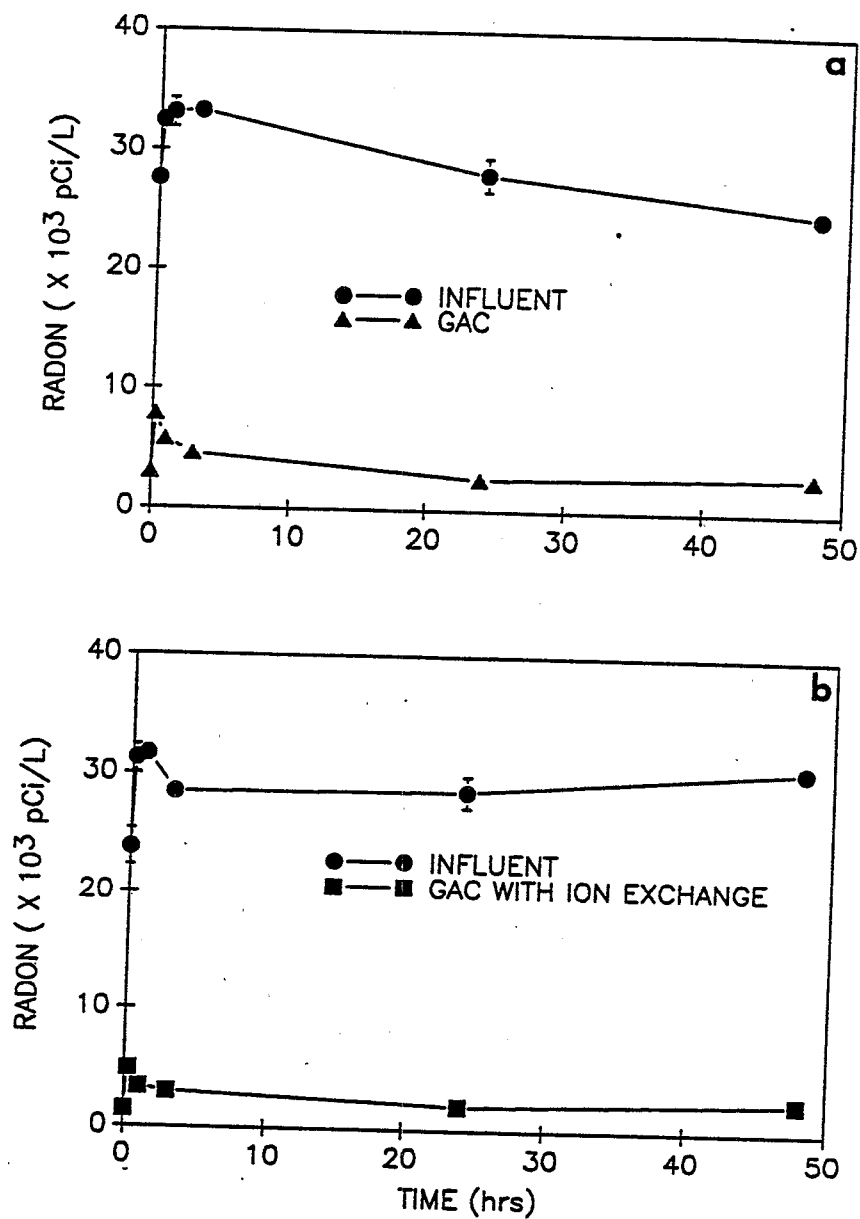


Figure 41. Influent and effluent radon activities after backwashing for the GAC without pretreatment (a) and the GAC with pretreatment (b).

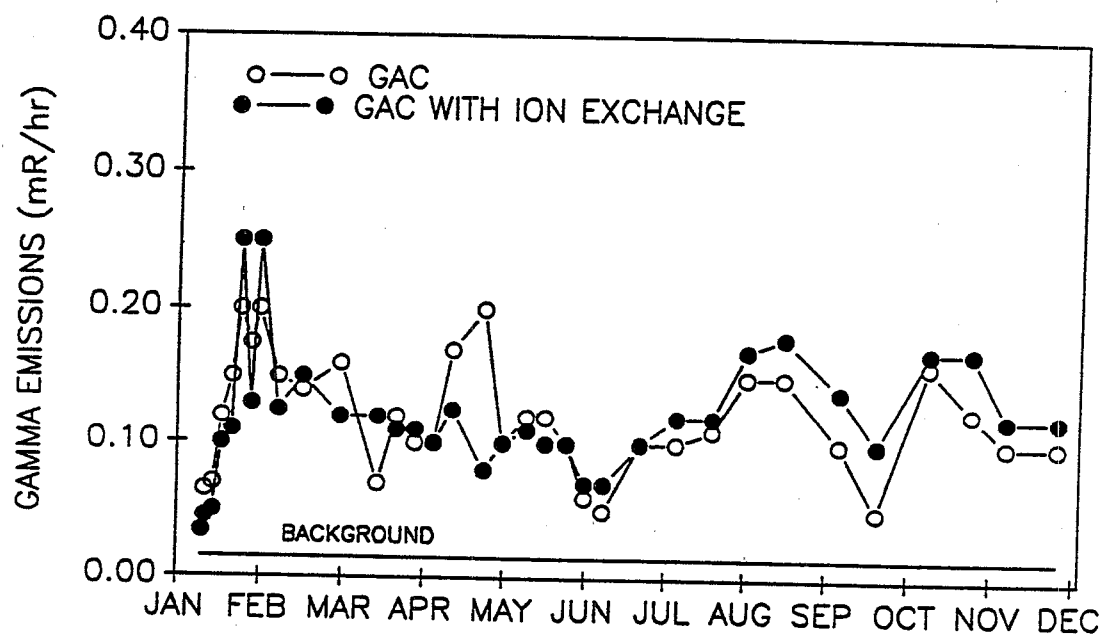


Figure 42. Gamma emissions measurements for the GAC systems at 1.5 m away from the units' surfaces.

Water jackets are often proposed to reduce the gamma exposure dose in the area surrounding the GAC tank. At the end of the study, the GAC unit with pretreatment was placed in the center of a 61 cm diameter, 136 cm high polyethylene plastic tank filled with water. Survey meter measurements were taken at the surface of the plastic tank surrounding the GAC unit (i.e., 30.5 cm away from the GAC tank itself) and 150 cm away from the GAC tank before and after the plastic tank was filled with water. These data indicated that the water jacket attenuated the gamma radiation by 14-17% at 30.5 cm. There was no measurable attenuation at 150 cm. Though the 14-17% decrease in potential gamma dose is substantial, it is not sufficient to eliminate the problems associated with residential radiation exposure when POE GAC units are used to treat ground water for radon, especially when the influent radon activity is high.

#### Uranium/Radium/Lead-210 --

At the end of the study, the GAC and the ion exchange units were cut open and samples of GAC were collected for high resolution gamma spectrometer analysis. The retention of radionuclides in these units was a concern because during the small community radon removal study (Kinner et al., 1990) it became apparent that the GAC was contaminated with substantial quantities of radium-226, lead-210 and uranium-238, and required special disposal practices.

All coring data were calculated in kg dry weight of GAC (based on percent moisture content) and reflect a composite of 2 subsamples of the GAC and ion exchange resin obtained at particular depths within the beds. Samples of virgin GAC and resin were also analyzed to assess background levels and the values obtained were subtracted out of all data presented. Radioactive standards were prepared using virgin GAC and resin spiked with lead-210.

Comparisons were made, when possible, between the predicted retention (based on average influent activity and average flowrate for the entire bed) and the coring data obtained for each radionuclide. The estimated adsorption usually corresponded fairly well to the coring data considering these estimates were based on average influent activities and total flow through the units and did not take into account the actual variations in these parameters occurring at the site. It is not possible to do an accurate mass balance on any of the elements sampled because of the natural variation in influent water quality and flowrate occurring in ground water supplies.

Uranium was removed from the water as it passed through the GAC without pretreatment ( $80 \pm 32\%$  removal), and through the ion exchange ( $73 \pm 23\%$  removal) and GAC with pretreatment ( $35 \pm 39\%$  removal). At the pH of the Derry water ( $6.03 \pm 0.34$  removal, range 5.25-6.86), the predominant uranium species was the neutral  $\text{UO}_2\text{CO}_3$  (Sorg, 1988). Since researchers (Bean et al., 1964) have demonstrated that the surface of GAC is primarily nonpolar with a net negative charge, adsorption should favor positively charged species. However, work by Weber (1972) has shown that positive species tend to be hydrophillic and are poorly adsorbed. Therefore, adsorption would be a maximum for neutral species. Based on these findings, it was expected that some uranium adsorption would occur in the GAC and ion exchange units. There was uranium removal observed in the ion exchange and GAC units during treatment (Figure

43) and there was good agreement between the coring data and the predicted uranium removal (Tables 10 and 11). [N.B., Excellent correlations were not expected between the predicted adsorption and the coring data because of the variation in influent radionuclide activities and the degree of extrapolation required when only 3 samples were taken over the entire depth of the filter beds.] Interestingly, more uranium was retained in the GAC without pretreatment, especially in the top of the bed. This can be attributed, in part, to the higher uranium loading to this GAC unit (i.e., the ion exchange removed some uranium from the water, so the load to the GAC with pretreatment was reduced). However, it is possible that some uranium may have been removed by co-precipitation with the iron in the water entering the GAC without pretreatment (S. Rydell; USEPA Region I; Boston, MA; 1990). The uranium retention correlated closely with the iron accumulation data (see discussion of iron).

The removal profile indicated that uranium was removed exponentially through the bed and as in the small community study would probably eventually approach exhaustion. Presently, there is no MCL set for uranium, but it is likely to be in the range 20 to 40 pCi/L (EPA, 1989a). Though the GAC has some capacity for adsorbing uranium, it seems to be related to pH, alkalinity and iron deposition and is not considered a viable treatment technique.

Based on the uranium coring data from the GAC unit without pretreatment, the carbon potentially exceeds the State of New Hampshire's de-minimus standards for (State of New Hampshire Radiological Health Program, 1983) uranium-238, but not for uranium-235 (both regulations are 58,410 pCi/kg,  $2.5 \times 10^{-5}$  Ci/m<sup>3</sup>). However, to confirm this, samples would need to be taken of the bed after it was completely homogenized to get a representative activity per unit mass. The data indicated that neither the ion exchange resin nor the GAC with pretreatment would probably exceed the de-minimus standards for uranium-238 or 235. According to the draft EPA Guidelines for Disposal of Drinking Water Treatment Plant Residues Containing Naturally-Occurring Radionuclides (1989b), the solid residues would fall in the range 30-300 pCi/g and could be placed in a stabilized landfill, or could be diluted with uncontaminated materials to an activity <30 pCi/g for use as construction fill or an agricultural soil conditioner or for deposition in a landfill.

A small amount of radium removal was detected through the GAC without pretreatment (Figure 44), while the GAC with pretreatment did not receive any detectable ( $\leq 0.10$  pCi/L) input of radium because of the efficiency of the cationic exchange resin (radium-226 removal >99%). As a result, it was difficult to make comparisons between the predicted radium-226 adsorbed and the coring data. The coring data indicated that the GAC did adsorb some radium-226 (Table 12), but there was no significant change in activity with depth in the bed ( $\alpha = 0.10$ ). The ion exchange unit adsorbed and retained substantial amounts of radium-226 even after the unit was regenerated (Table 12). This was not surprising since the resin was designed for adsorption of cations and a certain degree of irreversible (chemical) adsorption would be expected.



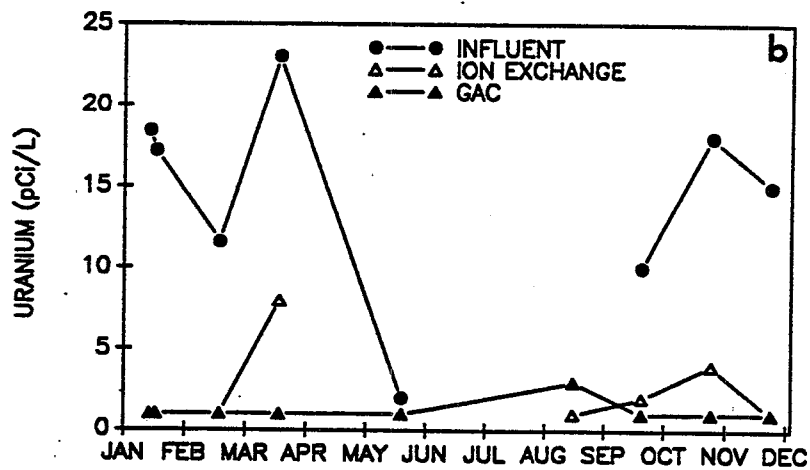
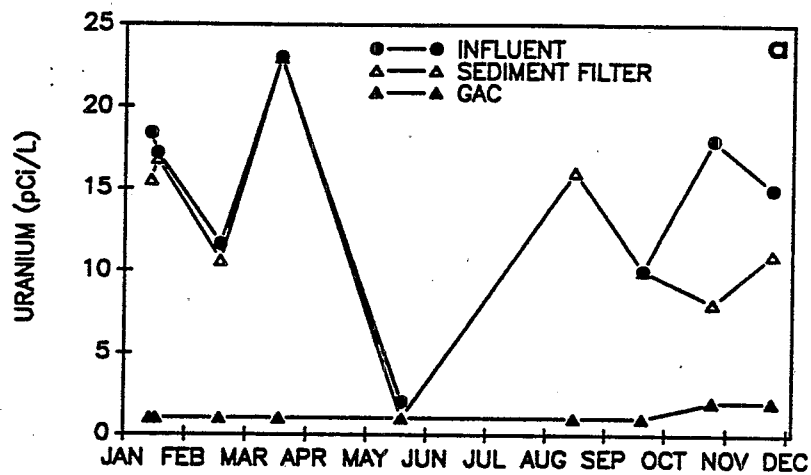


Figure 43. Uranium for the GAC without pretreatment (a) and the GAC with pretreatment (b).

TABLE 10. COMPARISON OF PREDICTED\* URANIUM ADSORBED TO THE CORING DATA FOR THE GAC UNITS

Location in Bed <sup>‡</sup>	Uranium-238 (pCi/kg <sup>+</sup> )	
	GAC Without Pretreatment	GAC With Pretreatment
Top	178,854	64,938
Middle	59,034	30,400
Bottom	25,956	11,475
Uranium-235 (pCi/kg <sup>+</sup> )		
Top	7,118	2,433
Middle	3,034	1,057
Bottom	1,184	1,124
$\bar{X}$ of U-238 + U-235 in Bed	79,684	33,216
Predicted U-238 + U-235 in Bed*	214,414	59,657

\*Predicted calculation based on total uranium as assessed by EPA Method 908.0 (EPA, 1980). Calculated using average total uranium activity and water flowrate measured during operating period.

<sup>+</sup>pCi/kg dry weight of GAC, based on percent moisture data.

<sup>‡</sup>In GAC without pretreatment, coring depths were top, middle = 43 cm, bottom = 93 cm. In the GAC with pretreatment, the coring depths were top, middle = 41 cm, bottom = 93 cm.

TABLE 11. URANIUM CORING DATA FOR THE ION EXCHANGE UNIT\*

Location in Bed <sup>‡</sup>	(pCi/kg <sup>+</sup> )	
	Uranium-238	Uranium-235
Top	19,221	1,866
Middle	8,126	1,944
<u>Bottom</u>	<u>8,614</u>	<u>2,416</u>
$\bar{X}$	11,987	2,075

\*Because of frequent regeneration, predicted values could not be determined.

<sup>+</sup>pCi/kg dry weight of resin, based on percent moisture data.

<sup>‡</sup>In ion exchange unit, coring depths were top, middle = 38 cm, bottom = 76 cm.

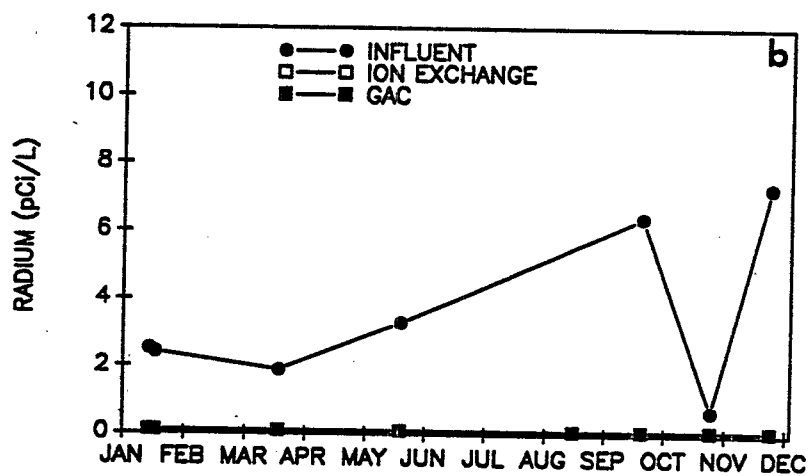
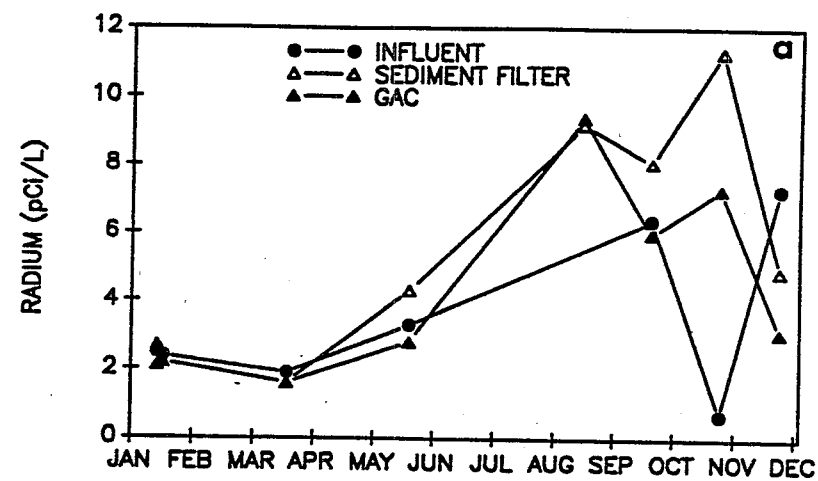


Figure 44. Radium for the GAC without pretreatment (a) the GAC with pretreatment (b).

TABLE 12. RADIUM CORING DATA FOR THE GAC AND ION EXCHANGE UNITS

Location in Bed <sup>+</sup>	Radium-226 (pCi/kg <sup>*</sup> )		
	GAC Without Pretreatment	Ion Exchange	GAC With Pretreatment
Top	715	10,189	240
Middle	651	21,027	534
<u>Bottom</u>	<u>786</u>	<u>21,773</u>	<u>379</u>
$\bar{X}$ in Bed	703	17,663	427

\* pCi/kg dry weight of resin, based on percent moisture data.

<sup>+</sup> In GAC without pretreatment, coring depths were top, middle = 43 cm, bottom = 93 cm. In ion exchange unit, coring depths were top, middle = 38 cm, bottom = 76 cm. In GAC with pretreatment, coring depths were top, middle = 41 cm, bottom = 93 cm.

It is well documented that radium is poorly adsorbed by GAC (Sorg and Logsdon, 1978) since it has the greatest ionic and electropositive nature of all Group II elements (Cotton and Wilkinson, 1980) rendering it extremely hydrophilic. Therefore, removal of radium by GAC adsorption alone is considered unfavorable (Sorg and Logsdon, 1978). It was hypothesized that the radium found in the GAC cores may have been removed by adsorption or ion exchange reactions occurring with other solid phases (e.g.,  $\text{Fe}(\text{OH})_3$ ,  $\text{MgCO}_3$ ) or organic matter deposited on the GAC. However, reactions with  $\text{Fe}(\text{OH})_3$  are considered unlikely because radium-226 activities were not significantly higher in the top of the GAC without pretreatment when compared to GAC samples deeper in the bed (see Iron Coring Data - Table 7).

While the GAC removed some radium from the water, the MCL for total radium is 5 pCi/L and GAC sorption should not be considered an alternative treatment technique. Based on the regulations established by the State of New Hampshire Radiological Health Program (1983), the GAC from the unit without pretreatment and the ion exchange resin would be considered low level radioactive waste with respect to radium-226 because they exceeded the de minimus standard of 44.39 pCi/kg ( $1.9 \times 10^{-8} \text{ Ci/m}^3$ ). The average data from the GAC unit with pretreatment was below this level. In the draft EPA Guidelines for Disposal of Drinking Water Treatment Plant Residues Containing Naturally - Occurring Radionuclides (1989b), only solid wastes containing >2000 pCi/g of radium-226 must be disposed of at a low level radioactive waste facility. The POE GAC generated in this study with radium-226 activities <3 pCi/g would not require special treatment. However, the ion exchange resin (10-22 pCi/g) would require disposal in a stabilized landfill.

The highest activities on the GAC came for lead-210, the long-lived progeny of radon (Table 9). The State of New Hampshire does not regulate lead-210, however, the draft EPA guidelines (1989b) have specified special treatment for activity levels of 30-2000 pCi/g. As with uranium, the carbon from both units would be in this range (GAC without pretreatment = 235 pCi/g; GAC with pretreatment = 246 pCi/g). Unless the GAC could be diluted with uncontaminated materials, it would need to be placed in a stabilized landfill.

The Carbdose 2.0 model (Keene and Rydell, 1989) predicts that the lead-210 adsorbed on the GAC (using an average influent radon activity = 35,620 pCi/L, a water flowrate = 1,122 L/day and a 90% removal efficiency) should be 956 pCi/g (wet carbon). Using the daily radon activity and water flowrate data collected over the course of the study, the predicted lead-210 adsorption (992 and 1,072 pCi/g (wet carbon) for the GAC without pretreatment and the GAC with pretreatment, respectively) was very similar to the Carbdose 2.0 model. However, the actual lead-210 adsorbed to the GAC was 74 to 75% less than the Carbdose 2.0 prediction. It is possible that some of the lead-210 was not retained by the GAC, but this conclusion cannot be verified because of the variability in radon loading and removal throughout the period of operation.

In addition, the ion exchange resin was contaminated with many radionuclides besides radium-226 and uranium-238 and 235. The cationic resin

probably retained many of the naturally-occurring radionuclides present in the raw water as they are usually cationic. It is also possible that some of these may have been removed by adsorption or ion exchange reactions occurring with other solid phases (e.g.,  $\text{Fe}(\text{OH})_3$ ,  $\text{MgCO}_3$ ) or organic matter in the ion exchange unit. It is interesting to note that the coring samples for the ion exchange unit were taken just after the unit had completed an entire regeneration program (Table 2). It appears that normal regeneration with brine will not completely remove the sorbed radionuclides. The water exiting the ion exchange unit during the brine regeneration part of the regeneration program was sampled on one day in November and contained substantial amounts of total uranium and radium-226 (Table 13) even after the 90 min brine regeneration process was completed. Disposal of this slurry should be carefully evaluated to determine the appropriateness of any alternative, including direct discharge into the residence's septic system or sewer.

### Aeration Techniques

#### Radon --

The diffused bubble unit consistently produced effluents with radon activities less than or equal to 200 pCi/L (Figure 45). This occurred even when the air flowrate was restricted because the diffusers accumulated iron precipitates (May-June, 1989). Removal efficiencies of this magnitude (>99%) are expected with this technique considering that (i) the influent radon activity was not exceptionally high, (ii) the blower provided an air to water ratio (A:W) of approximately 119:1 assuming a water flowrate of 9 L/min through the unit, and an air flowrate of  $1.08 \text{ m}^3/\text{min}$ , and (iii) the bubble size was relatively small (diffuser hole diameter = 0.64 mm). The data agree with results obtained by other researchers (Lowry et al., 1987; Lowry, 1988).

The bubble plate unit also produced a very high quality effluent (>99% radon removal) except on a few occasions. This is similar to results reported by LaMarre (1988 and 1989). The unit experienced several mechanical problems throughout the course of the study (e.g., solenoid valve failure, pump failure, leaking plumbing). The most detrimental problem with respect to radon removal was the clogging of the air intake filter for the blower. This reduced the air flow to the bubble plate chamber and resulted in the higher effluent radon activities in August through December. The manufacturer suggested yearly inspection of the filter, however, that was insufficient in our application. Once this problem was corrected, the unit began to produce effluent containing  $\leq 200 \text{ pCi/L}$  again. The A:W ratio for the bubble plate was 156:1 (assuming a water flowrate of 22.7 L/min and an air flowrate of  $3.54 \text{ m}^3/\text{min}$ ). Unfortunately, the bubble plate unit used in this study was not equipped with a device to inform the operator that the air flowrate was restricted. Therefore, inadequate air flow occurred until water quality monitoring results showed that the effluent radon activity in the water was unacceptable.

It is not surprising that both of the aeration units worked well at removing the amount of radon present in the raw water. They have high A:W ratios compared to those found in other aeration units optimized for radon

TABLE 13. TOTAL URANIUM AND RADIUM IN THE BRINE EXITING THE  
ION EXCHANGE UNIT DURING BRINE REGENERATION\*

Time in Brine Regeneration Process (min)	Total Uranium <sup>+</sup> (pCi/L)	Radium-226 <sup>**</sup> (pCi/L)
20	1,179	1,498
50	918	772
90	187	223

\* The brine regeneration process is 90 min long. It is one step in the entire ion exchange unit's regeneration program. See Table 2.

<sup>+</sup> Analyzed using EPA method 908.0 (EPA, 1980).

<sup>\*\*</sup> Analyzed using EPA method 903.1 (EPA, 1980).



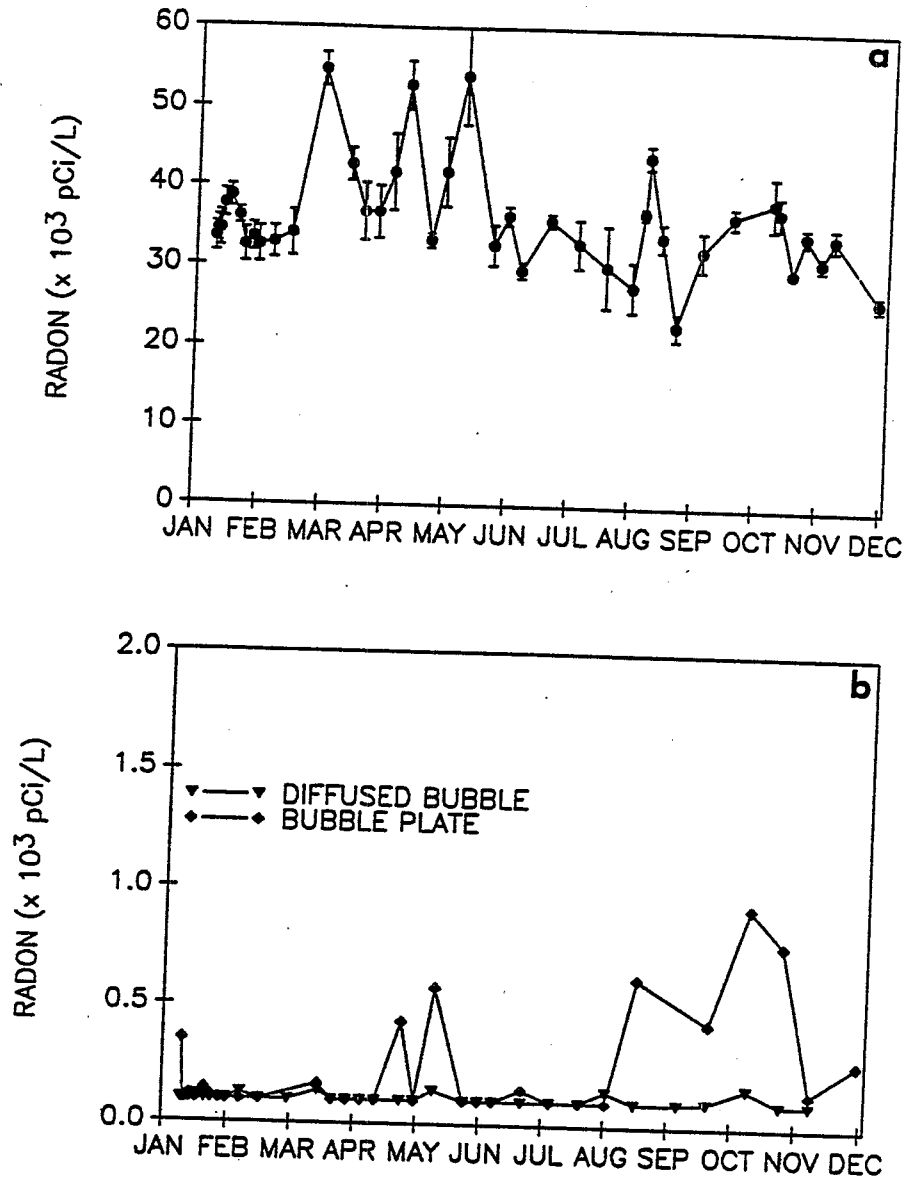


Figure 45. Radon activities for the influent (a) and the effluent from the aeration units (b). (note scale difference).

removal (Kinner et al., 1990). However, the blowers used in these POE units are the most cost effective based on overall efficiency.

#### Air Monitoring --

The air monitoring study was conducted to determine if there was a detectable effect of the exhaust from the aeration units on the ambient air radon activities surrounding the building. Detectors located at a site ~5 km from the Derry pumphouse registered radon activities  $\leq 0.3$  pCi/L (the detection limit of the alpha-track monitors). The detectors located 1.5 to 24 m away from the pumphouse all registered  $\leq 0.3$  pCi/L. [N.B., All of these detectors were located above the elevation of the vents from the aeration units.] Monitors inside the pumphouse indicated that the airborne radon activities were in the range 0.9 to 1.7 pCi/L. This is not atypical for a building in this region with a dirt floor. Some of the activity may have resulted from the treatment units, however, it was not possible to determine this. The detectors located 1.35 m directly under the vents for the aeration units registered 1.4 to 2.1 pCi/L. Considering that the radon exiting to vents should have been approximately 228-298 pCi/L this dilution of  $10^2$  is expected. If the exhaust from POE units is vented above a home's roof-line there should be sufficient dilution to get the radon activity in the plume diluted to background levels very quickly.

#### ECONOMICS

A detailed economic evaluation of the technologies examined in this project for removal of radon using POE treatment was performed using conventional engineering economic practices. The economic evaluation assumed all water system components (e.g., well, pressure tank, piping) would already be in place and therefore, only the costs related to installation and operation of radon removal systems are presented. Costs have been divided into two major categories: capital costs and operation and maintenance (O&M) costs. Capital costs include equipment and installation costs (obtained from records of actual expenditures made during this project) plus 15% for engineering and subcontractor fees and 15% for miscellaneous contingencies. The latter percentages have been recommended by USEPA (1987) for use in estimating POE treatment costs.

Operation and maintenance costs include power, labor, maintenance and administrative costs. Power costs were calculated based on equipment horsepower, operating efficiency, operation period and electrical power cost. An electrical power cost of \$0.10157/kW-hr was used based on a Public Service of New Hampshire (PSNH) Class G rate scale for household usage below 5 kW (J.R. Prescott, Public Service of New Hampshire, personal communication, 1990). Labor and equipment maintenance costs were estimated based on a survey of available POE service records for carbon and aeration units presently operating in New Hampshire and Maine. Administrative costs were calculated as the sum of 20% and 25% of the labor and maintenance costs, respectively (Cummins, 1987).

For comparative purposes, annual costs and production costs were developed for each treatment system. The production costs were expressed in conventional units of \$/1,000 gallons to be consistent with those reported in other studies. The annual cost was computed as the sum of the amortized capital cost and the O&M cost. The amortized capital cost is the total capital cost amortized over a 5 year time period at a 9% interest rate. A 5 year time period was chosen since it reflects a typical home equity loan (i.e., typical means of financing POE costs) payback period (D.L. Perry, Internal Revenue Service, Consumer Information Service, personal communication, 1990). The interest rate of 9% reflects the current U.S. Treasury Bill (T-Bill) interest rate. Production costs were calculated by dividing the annual cost by the volume of water treated per year assuming the system was operated at a design flow of  $1.02 \text{ m}^3/\text{day}$ .

All cost figures were updated to first quarter 1990 dollars using the ENR Construction Cost Index (CCI). The 1967 base year CCI index for first quarter 1990 is 435.

The cost estimates presented in this report are intended to give a general indication of the economics of the POE radon removal technologies studied. Specific treatment requirements will vary from site to site and may not be accurately reflected by the systems or assumptions used in this economic analysis.

The cost estimates for the GAC POE systems with and without pretreatment (ion exchange) are shown in Table 14. Based on a design flow of  $1.02 \text{ m}^3/\text{day}$ , the production costs for GAC without and with pretreatment are \$9.31/1,000 gallons and \$12.25/1,000 gallons, respectively. The total production costs including disposal of the GAC/resin are estimated to be \$9.88/1,000 gallons for GAC without pretreatment and \$13.40/1,000 gallons for GAC with pretreatment.

It should be noted that the O&M cost estimates assume power costs are negligible and that backwash or ion exchange regenerant streams can be discharged without additional treatment costs (e.g., to the septic system).

The cost of GAC/resin disposal assumes it must be handled as a regulated low level radioactive waste and is based on a disposal cost estimate of \$4,400/ $\text{m}^3$  (1990 dollars) of GAC/resin (R.L. Kennedy, General Dynamics Service Company, Reactor Plant Services, personal communication, 1990). It was assumed that this cost would be incurred at the end of the 5 year life. Thus, the cost was adjusted to a future cost using a 10% annual inflation rate and this future cost was then amortized (9% for 5 years) to an annual cost of \$340/ $\text{m}^3\text{-yr}$  or \$57/yr for the GAC without pretreatment and \$115/yr for GAC with pretreatment. This annual cost represents an additional production cost of \$0.57/1,000 gallons for the GAC without pretreatment and \$1.15/1,000 gallons for the GAC with pretreatment. This cost will be higher than the actual production costs if the GAC and resin can be disposed of in a stabilized landfill.

TABLE 14. COST ESTIMATES FOR THE GAC POE TREATMENT SYSTEMS AT DERRY, NH

Item	Total Cost	
	(1st Quarter 1990 Dollars)*	
	GAC Without Pretreatment	GAC With Pretreatment
<b>CAPITAL COSTS</b>		
Equipment	\$ 785	\$1,500
Installation	1,200	1,400
Total Direct Cost	<u>\$1,985</u>	<u>\$2,900</u>
Engr./Sub. Fees	298	330
Contingencies	<u>298</u>	<u>330</u>
TOTAL CAPITAL COST	\$2,581	\$3,560
AMORTIZED CAPITAL COST (Annual)	\$ 664	\$ 916
<b>ANNUAL O&amp;M COSTS</b>		
Power	NA <sup>+</sup>	NA <sup>+</sup>
Maintenance <sup>#</sup>	160	185
Labor	45	50
Administrative	<u>49</u>	<u>56</u>
TOTAL ANNUAL O&M COST	\$ 254	\$ 291
TOTAL ANNUAL COST	\$ 918	\$1,207
TOTAL PRODUCTION COST (1.02 m <sup>3</sup> /day design flow)	\$9.31/1,000 gal	\$12.25/1,000 gal
GAC/RESIN DISPOSAL COST**	\$0.57/1,000 gal	\$1.15/1,000 gal
TOTAL PRODUCTION COST WITH DISPOSAL	\$9.88/1,000 gal	\$13.40/1,000 gal

\* Based on ENR Construction Cost Index = 435, Base Year 1967 = 100.

+ Additional power costs incurred by operation of the GAC systems are considered negligible.

# Based on survey of existing carbon POE systems. Includes brine solution regeneration of ion exchange unit.

\*\* Based on estimated disposal cost of \$340/m<sup>3</sup>-yr (assuming it is classified as a low level radioactive waste) and the design flow.

Cost estimates for the diffused bubble and bubble plate aeration systems are shown in Table 15. These data indicate that the total production costs for the diffused bubble and bubble plate aeration systems were \$22.58/1,000 gallons and \$26.74/1,000 gallons, respectively. The major difference in cost for the two aeration systems resulted from the differential in retail price of the equipment.

A major assumption implicitly made in the economic analysis of the aeration systems is that the radon present in the off gas will disperse in the atmosphere and will not require additional treatment. Although the economic analysis does account for the cost of piping the radon vent above the average home roof line (i.e., 11 m), no additional costs for auxiliary blowers or air treatment are included. If subsequent treatment is required to meet federal or state air quality standards, then the cost estimates could be significantly higher.

It should be noted that in comparison to total production costs for public water supplies the POE costs are high. The production costs for the individual POE systems are higher because (i) there is no economy of scale, and (ii) there will not be a quantity discount on the equipment when purchased for an individual well water supply.

#### OVERALL EVALUATION OF THE POE SYSTEMS

##### GAC

Of the three systems evaluated, the GAC requires the least owner maintenance, is the easiest to operate, and is the least expensive with respect to capital, and operation and maintenance costs (even when low level radioactive waste disposal costs are included). However, neither GAC system consistently produced effluent radon activities in the range of the proposed MCL (200-2,000 pCi/L). The data obtained in our study indicate that the only condition where POE GAC systems would produce effluent in this range would be if the influent activity were low (e.g.,  $\leq 5,000$  pCi/L). Influent activities  $\leq 5,000$  pCi/L would also result in lower gamma emissions from the GAC system as noted by Rydell et al. (1989) and yield acceptable levels of exposure dose (Rydell et al., 1989). Water jacket shielding could be used as an added measure of safety, but it would make accessibility to the unit difficult if repairs or maintenance were required. At such low influent loadings, the small reduction in gamma exposure dose from the water jacket would have a minimal effect on overall exposure.

As noted in the small community radon study, the operation of GAC systems usually requires either pretreatment and/or backwashing to prevent fouling resulting from accumulation of particulates and metal precipitates or fouling by bacteria and organic matter. We also hypothesized from the small community data that iron precipitates, bacteria or organics could limit the effective life of the GAC bed. Comparing the data from the GAC units with and without cationic pretreatment, it appears that retention of iron precipitates in the bed could shorten the life of the GAC with respect to radon removal and make it more susceptible to changes in loading. Both beds were similarly fouled with bacteria and organic matter. Turbidity was removed by the ion exchange

TABLE 15. COST ESTIMATES FOR AERATION POE TREATMENT SYSTEMS AT DERRY, NH

Item	Total Cost (1st Quarter 1990 Dollars)*	
	Diffused Bubble	Bubble Plate
<b>CAPITAL COSTS</b>		
Equipment	\$2,215	\$3,295
Installation	955	955
Total Direct Cost	\$3,170	\$4,250
Engr./Sub. Fees	476	638
Contingencies	476	638
TOTAL CAPITAL COST	\$4,122	\$5,526
AMORTIZED CAPITAL COST (Annual)	\$1,060	\$1,421
<b>ANNUAL O&amp;M COSTS</b>		
Power	80 <sup>+</sup>	54 <sup>#</sup>
Maintenance**	345	368
Labor	545	583
Administrative	195	209
TOTAL ANNUAL O&M COST	\$1,165	\$1,214
TOTAL ANNUAL COST	\$2,225	\$2,635
TOTAL PRODUCTION COST (1.02 m <sup>3</sup> /day design flow)	\$22.58/1,000 gal	\$26.74/1,000 gal

\* Based on ENR Construction Cost Index = 435, Base Year 1967 = 100.

<sup>+</sup> Based on input power of 0.5 Hp for blower operating 3.5 hr/day, 0.5 Hp for pump operating 2.3 hr/day, and an electric rate of \$0.10157/kW-hr.

<sup>#</sup> Based on input power of 0.33 Hp for blower operating 2.4 hr/day, 0.5 Hp for pump operating 2.3 hr/day, and an electric rate of \$0.10157/kW-hr.

\*\* Based on survey of existing service contracts for aeration POE systems in Maine and New Hampshire.

unit lowering that load to the subsequent GAC unit. Obviously, in POE applications where iron and manganese concentrations are high, ion exchange pretreatment is essential. However, its use is not without problems; specifically the contamination of the resin with long-lived radionuclides and the disposal of the heavily-contaminated backwash water and regenerant brine. If frequent backwashing of the GAC unit and use of a sediment filter can limit the accumulation of particulates and metal precipitates in the GAC bed, then ion exchange pretreatment should be avoided.

One of the primary conclusions of the small community radon removal study was the need to have sufficient data on variation in water flowrate and raw water radon activity. Based on the loading experiments, this seems to be somewhat less important for POE GAC units, especially if they are used to treat water with  $\leq 5,000$  pCi/L of radon where excess GAC can be supplied for little extra cost. At higher loadings, however, the GAC units may not be able to dampen the excess radon applied without some increase in effluent activity.

One of the ancillary problems associated with GAC treatment systems is the retention of longer-lived radionuclides, such as uranium-238, radium-226 and lead-210, in quantities which may dictate that the GAC must be disposed of in a special manner. This issue may prohibit the use of GAC in some applications where uranium and radium are present in large quantities, however, even if they are absent, lead-210 will always accumulate in the GAC as it is the long-lived progeny of radon. A more thorough evaluation must be made to determine whether for POE applications where the radon activity is  $\leq 5,000$  pCi/L the benefits of GAC (e.g., cost, ease of operation and maintenance) are outweighed by problems associated with specialized handling and disposal.

#### Aeration Techniques

Both the bubble plate and the diffused bubble POE units are very efficient ( $>99\%$ ) at removing radon from the water even at relatively high concentrations as demonstrated by this study and those of other researchers (Lowry et al., 1987; Lowry, 1988; LaMarre, 1988 and 1989). It appears that they will be able to meet an MCL of 200-2,000 pCi/L in most cases primarily because of the high A:W ratios used. Variations in influent radon activity and water flowrate should be handled without a significant increase in effluent radon activity.

There are several problems associated with the aeration treatment techniques. The primary issue is iron oxidation which occurs readily in these units. Even at iron concentrations below 1.0 mg/L, iron precipitates can form and accumulate in the units and/or be released in pulses to the residence when the unit is started to meet demand. In the diffused bubble unit, iron accumulation on the diffusers caused a gradual decrease in the air flowrate. An attempt was made to clean the diffusers using a low pH solution (sodium hydrosulfite, pH = 3.67) as recommended by the manufacturer. This did not improve performance, so the diffusers were replaced in June after 6 months of operation. The problem did not recur during the remainder of the study.

In order to avoid problems with iron precipitation in the units or problems within the residence, iron treatment will probably be required in almost all POE applications using aeration techniques. If the raw water is pretreated to remove iron before it enters the aeration device, precipitate problems should be completely avoided. This may be necessary in the diffused bubble units to prevent the diffusers from clogging. However, if pretreatment involves ion exchange resins, the problems previously discussed, such as radionuclide retention, must be solved. Sand filtration has been installed in some POE applications following bubble plate aeration units. These filters are designed to remove the iron precipitates formed during the aeration process. Before this alternative is used widely, the chemistry/biology of the filters should be examined to insure that they are effective and do not have problems with radionuclide retention associated with organic matter or solid phases (e.g.,  $\text{Fe}(\text{OH})_3$  or  $\text{MgCO}_3$ ). Further, the required backwashing frequency and related costs of these units should be thoroughly evaluated prior to widespread use.

POE aeration units are more expensive with respect to capital and operation and maintenance costs as compared to GAC units. In addition, they require much more frequent maintenance to insure that an adequate air flowrate is maintained and an extra pump is needed to repressurize the water system. It is particularly important to maintain an adequate air flowrate and hence, the air intake filter to the blowers should be cleaned frequently, every 1-3 months or more in dusty locations. There should be gauges which the owner can monitor to insure the proper air pressure/flowrate is maintained. This is not a surrogate for radon monitoring, but is the only way a homeowner could check that the air flowrate is correct. Addition of audible alarms to warn the homeowner of potential low air flow or pump failure is necessary, as the units will usually be in a remote location.

Proper venting of the aeration units is important. As demonstrated in this study, the plume is diluted fairly rapidly. However, the off-gas stack should be vented above the roofline to prevent any radon from re-entering the home. Placement of external auxiliary blowers may be required to produce adequate flow in these vent pipes.

During operation, the blowers and pumps associated with the aeration units are very noisy. Either the units should be put in a remote location or some soundproofing may be required, so that homeowners are not tempted to turn the units off to avoid the noise. In addition, the secondary jet pump required by the aeration systems will have a low pressure cut-off feature. This feature protects the pump from damage in the event of air binding due to the loss of system pressure (e.g., a power failure). Although the feature is required to avoid costly pump replacement, it will be a nuisance to the owner since it will require manual system restart. It is recommended that directions for the proper restarting procedure be clearly displayed on the unit. Despite these efforts, the low pressure cut-off feature may lead owners to by-pass the treatment system.



### Summary Evaluation for POE Systems

There were problems with the bacterial numbers in the effluent from all of the units tested. Depending on EPA and state regulations, it may be necessary to disinfect the water before use to avoid public health problems.

It should be noted that none of the units were tested to evaluate its performance at lower radon loading rates. In the small community radon removal study, it was stressed that extrapolation of results in full-scale application should not be made to systems with much lower influent activities. This is probably not as important for the POE units because they are usually oversized (e.g., excess GAC or high A:W ratios), but it should be considered.

Finally, frequent monitoring of the effluent quality of any POE unit should be stressed to the homeowner. Because radon cannot be detected by taste, smell or any other human sense, there is a potential for it to be reintroduced into the water supply without the homeowner knowing it if a POE unit fails. Traditionally, conventional engineering wisdom has suggested that using POE treatment to protect public health is only viable as a short term solution due to lack of proper maintenance and monitoring by the homeowner. Since widespread use of POE treatment units for radon removal is likely, it is vital that water analyses of the effluent at the tap be conducted at least every 3 months to insure risk reduction is maintained.

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APPENDIX A  
SUMMARY OF QA/QC DATA

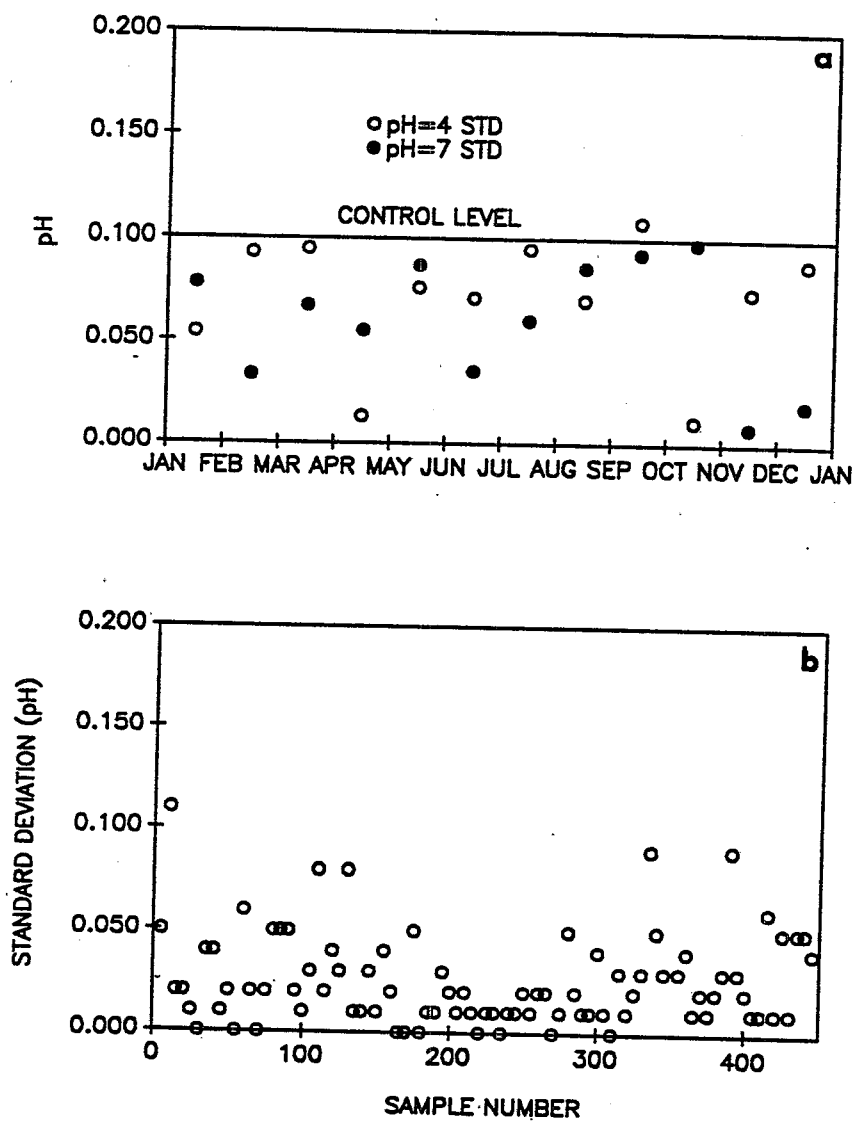


Figure A-1. QA/QC accuracy (a) and precision (b) for pH measurements.

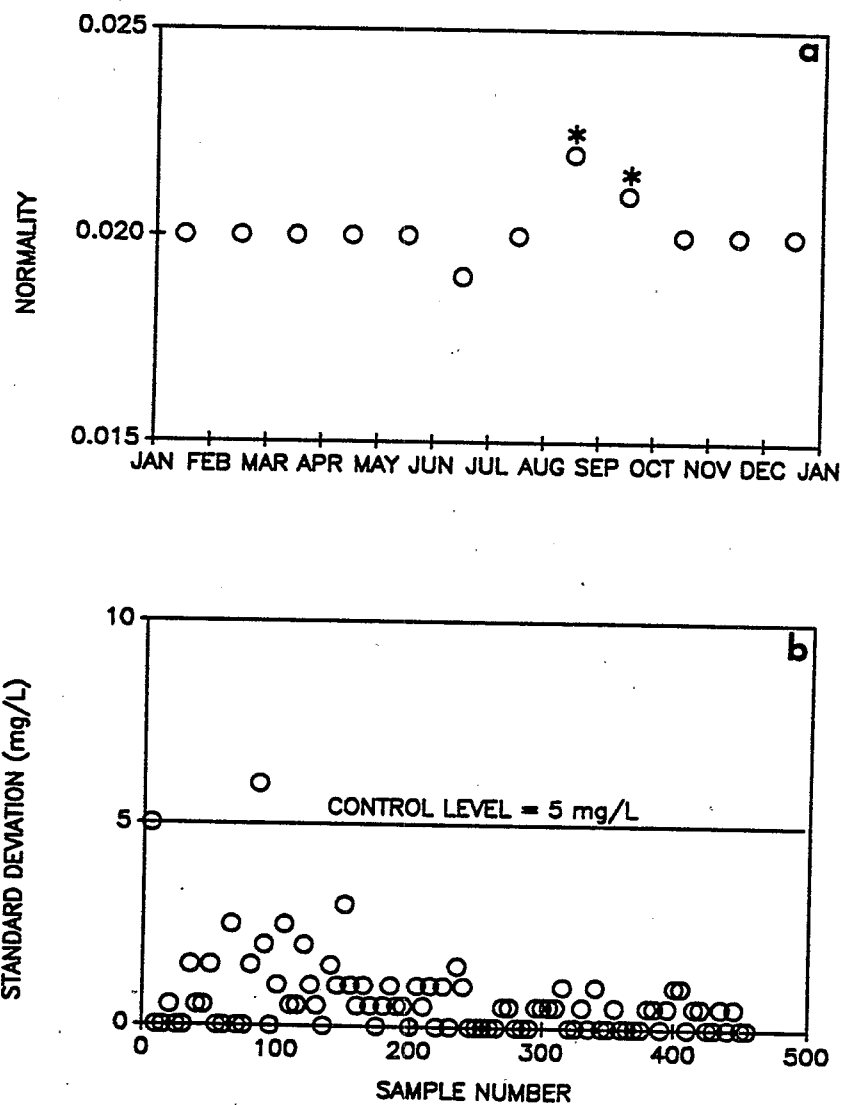


Figure A-2. QA/QC normality of titrant (a) and precision (b) for alkalinity measurements. (\* denotes new solution)

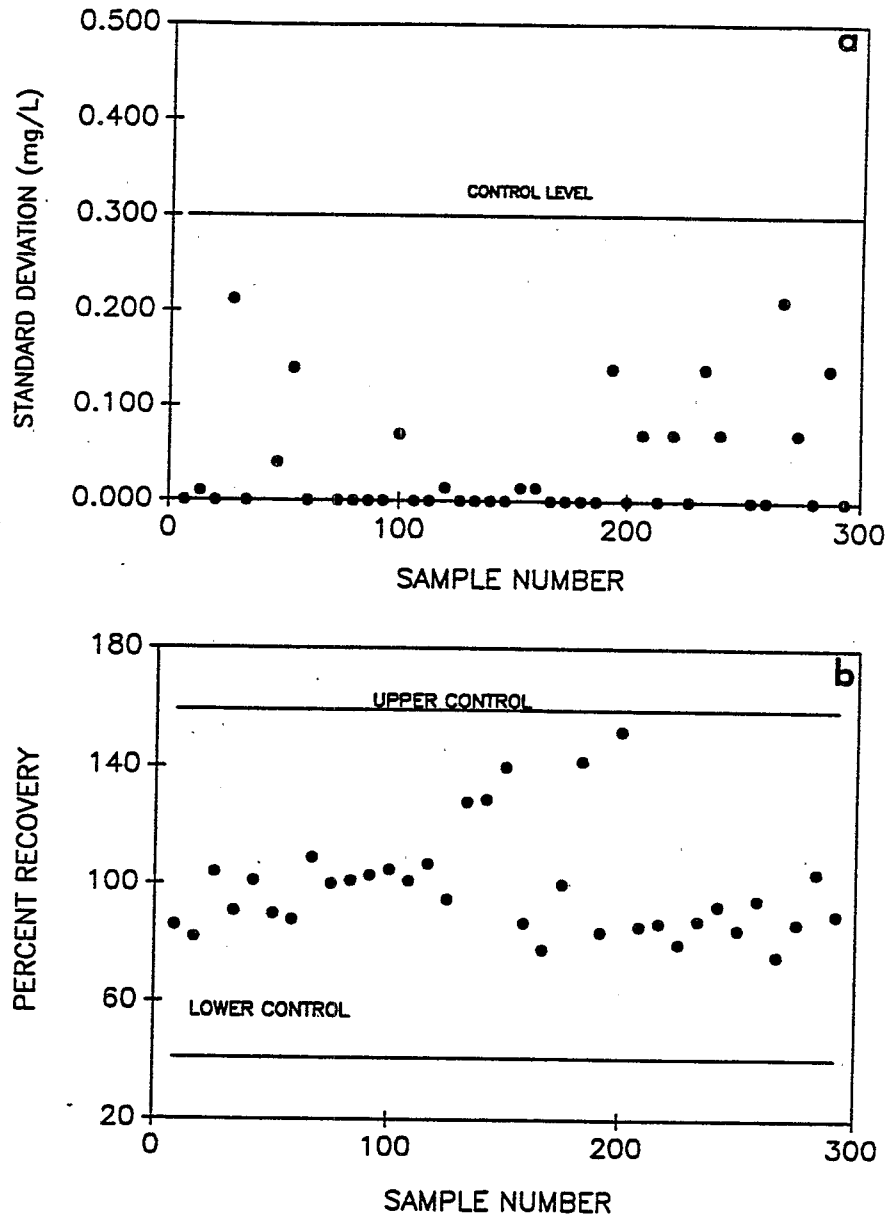


Figure A-3. QA/QC precision (a) and accuracy (b) for calcium measurements.



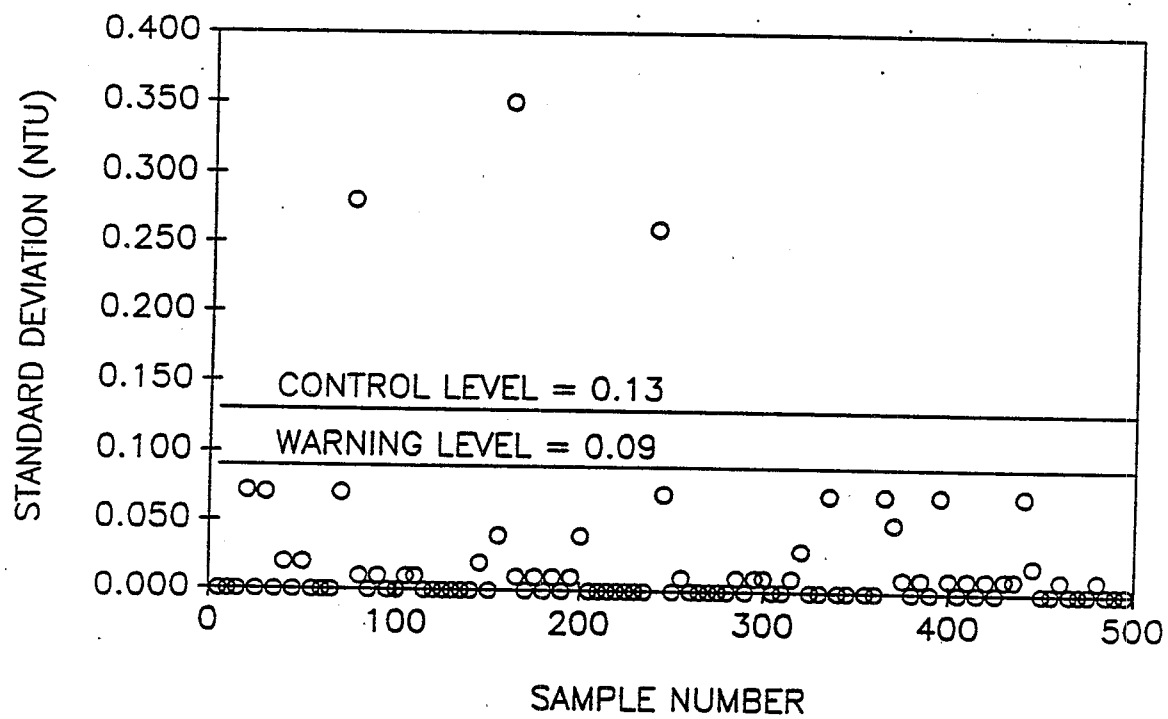


Figure A-4. QA/QC precision for turbidity measurements.

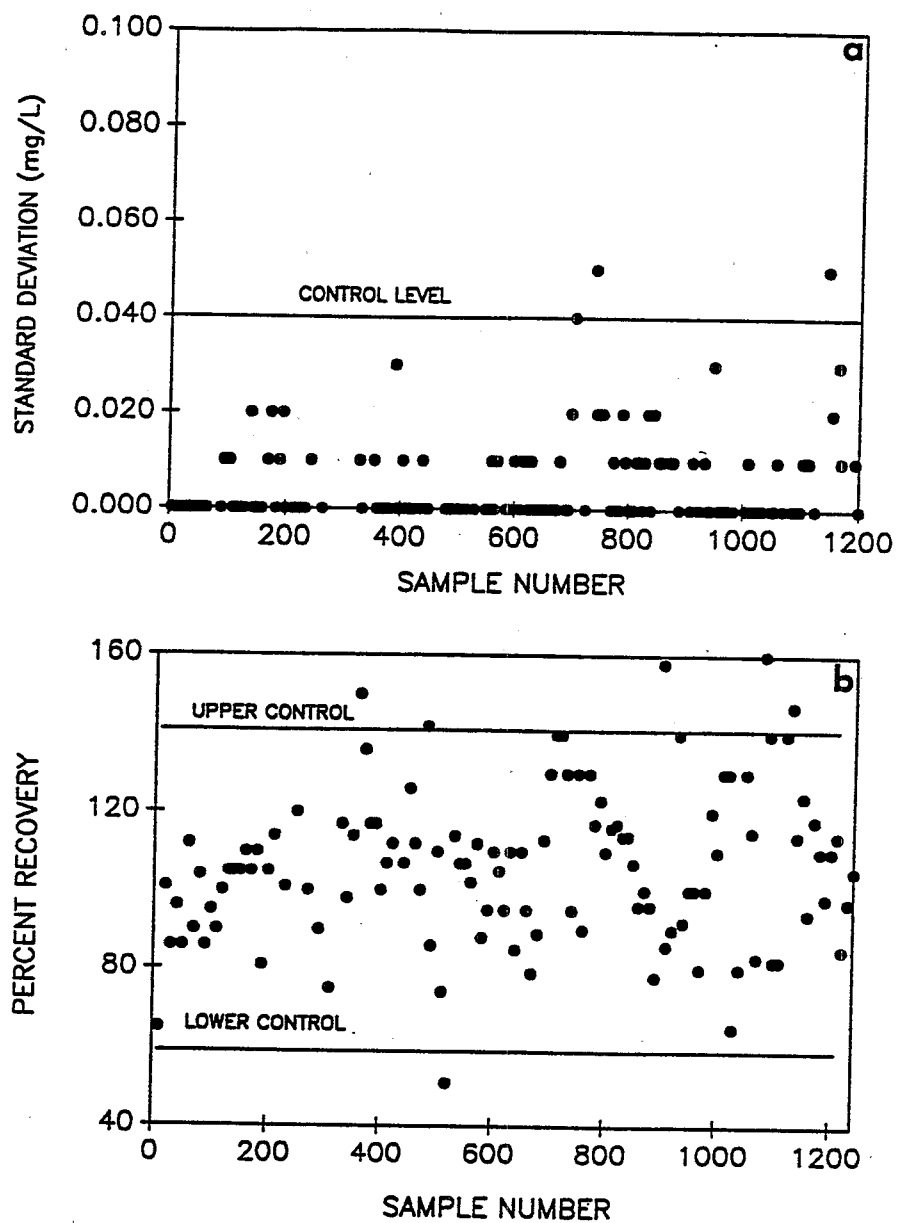


Figure A-5. QA/QC precision (a) and accuracy (b) for iron measurements.

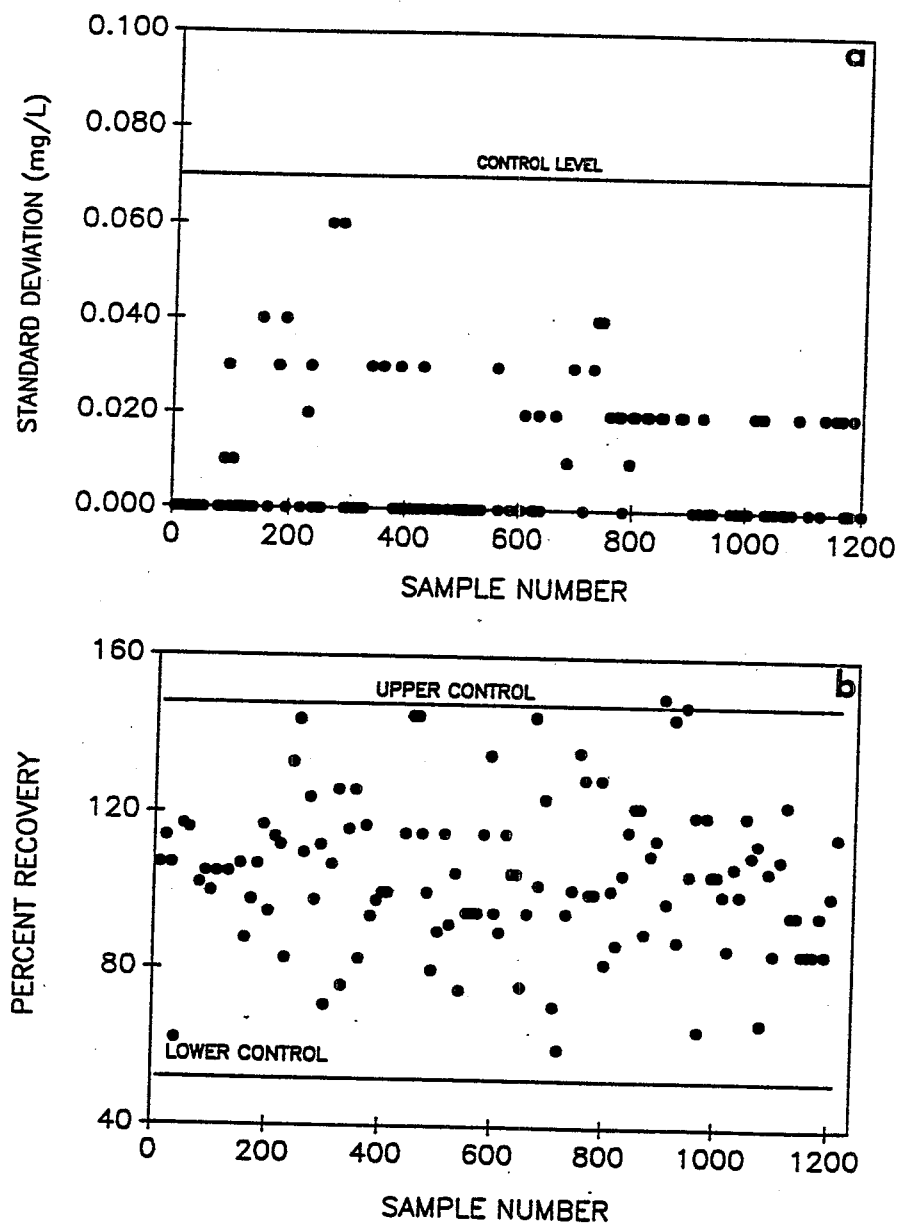


Figure A-6. QA/QC precision (a) and accuracy (b) for manganese measurements.

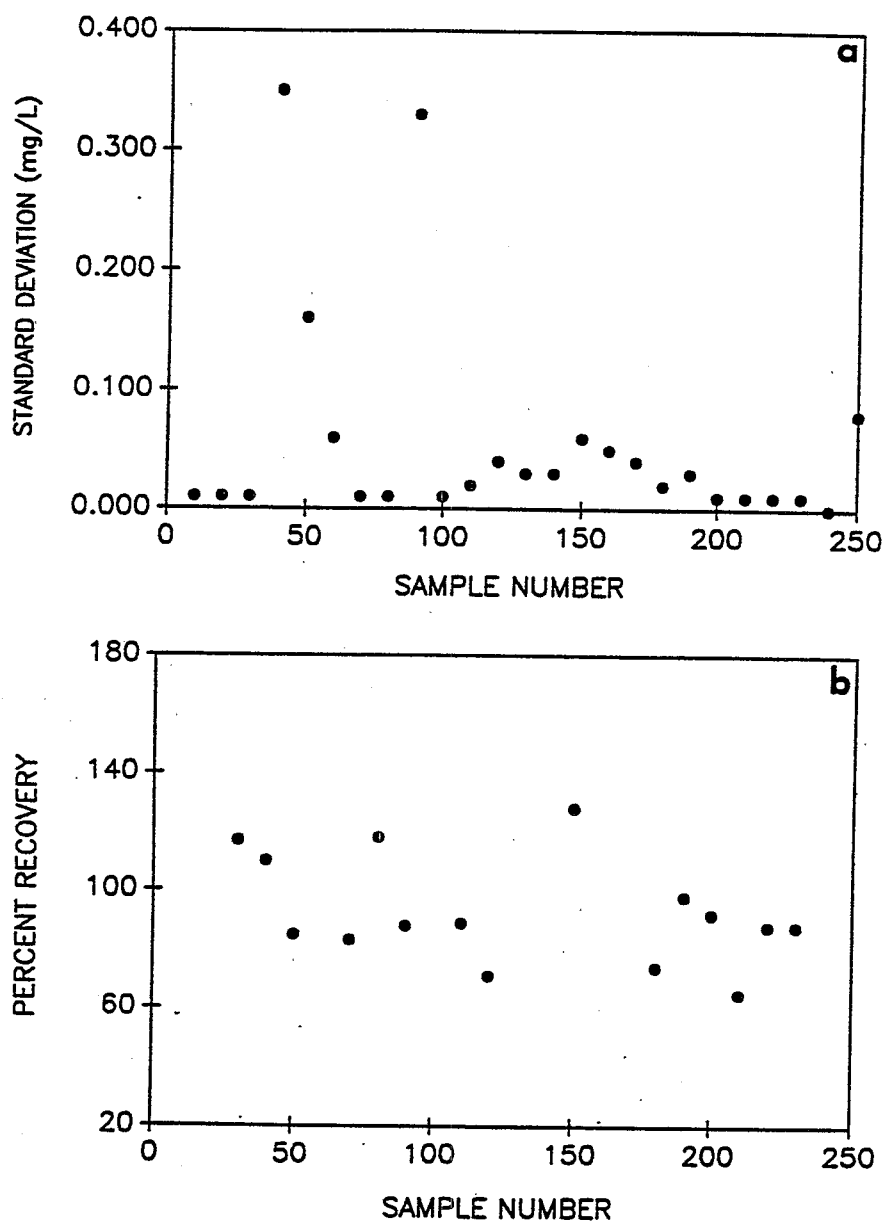


Figure A-7. QA/QC precision (a) and accuracy (b) for NPDOC measurements.

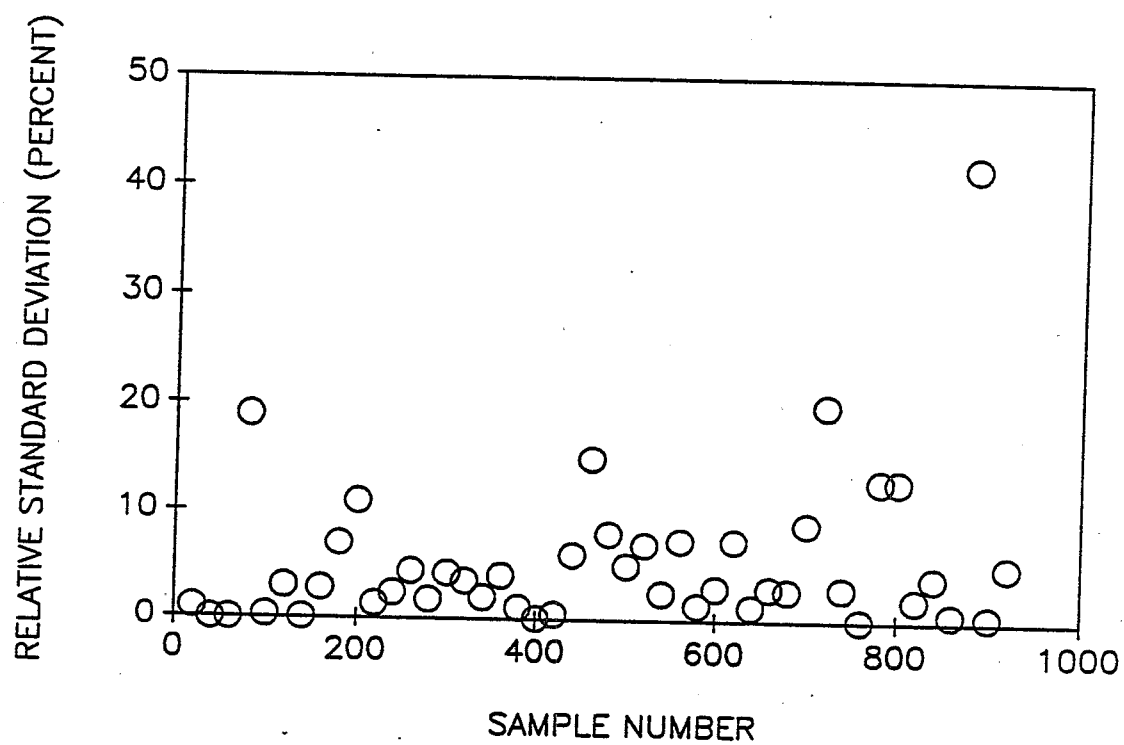


Figure A-8. QA/QC precision for radon measurements.

## APPENDIX B

### SUMMARY OF LIQUID SCINTILLATION COUNTER PROGRAM

The program outlined below was obtained from the operations manual for the Beckman (Fullerton, CA) LS 7000 liquid scintillation counter used in this research project. It is library program #6 for this instrument.

Unmodified Count Time		10 min for all samples except 50 min for effluent from aeration units	
Channels	Counted	Lower Limit	Upper Limit
1	$2.00\sigma\%$ *	0	397
2	$2.00\sigma\%$ *	397	940
Sample Channels Ratio		No	
H Number Calibration**		1 time (in channels 1 & 2)	
Automatic Quench Compensation		Yes	
Data Printout Units		cpm	

\* $2.00\sigma\% = 200/\sqrt{N}$  where  $N$  = total number of counts obtained at the time of calculation.

\*\*The H-number quantifies quench and indicates the effect of interferences on the counting efficiency. Automatic quench compensation uses an internal cesium-137 source to generate an H-number for each sample, which the liquid scintillation counter uses to adjust the count rate generated in correspondence to the quenching.

# APPENDIX C

## SUMMARY OF THE RAW WATER CHARACTERISTICS AT THE DERRY, NH POE SITE

Constituent	Concentration*
Radon	35,620 $\pm$ 6,727 pCi/L
pH	6.24 $\pm$ 0.19
Temperature	11.8 $\pm$ 2.5°C
Alkalinity	34 $\pm$ 19 mg/L as CaCO <sub>3</sub>
Calcium	15.5 $\pm$ 1.15 mg/L
Turbidity	1.04 $\pm$ 0.94 NTU
Microbial Numbers	30,400 $\pm$ 29,500 CFU/100 mL
NPDOC <sup>†</sup>	1.30 $\pm$ 0.28 mg/L
Total Iron	0.40 $\pm$ 0.27 mg/L
Soluble Iron	0.32 $\pm$ 0.22 mg/L
Total Manganese	0.36 $\pm$ 0.12 mg/L
Soluble Manganese	0.35 $\pm$ 0.11 mg/L
Uranium	14.4 $\pm$ 6.5 mg/L
Radium	3.5 $\pm$ 2.4 pCi/L

\*Mean  $\pm$  Standard Deviation

<sup>†</sup>NPDOC = Non-Purgeable Dissolved Organic Carbon

## APPENDIX D

### METHODS OF CALCULATION OF LEAD-210 ADSORPTION

#### I. Calculation of Lead-210 activity from gamma counter data using channels 89-96.

$$A' = \frac{\text{Net Peak Counts}}{(t) (m) (E) (I_g)}$$

where  $A'$  = activity (dpm/g GAC dry weight)

Net Peak Counts = (Adjusted Peak Counts - Adjusted Compton Counts)

Adjusted Peak = (Sample Peak - Background Peak)  
Counts                      Counts                      Counts

Adjusted Compton = (Sample Compton - Background Compton)  
Counts                      Counts                      Counts

$t$  = time sample counted (min)

$m$  = mass of sample (g)

$E$  = efficiency factor based on counts obtained from Lead-210 standard sorbed to equivalent volume of virgin GAC (cpm/dpm)

$I_g = 0.04$  = amount of Lead-210 emissions which are gamma radiation

$$A = A' \cdot \frac{1 \text{ pCi}}{2.22 \text{ dpm}} \cdot \frac{1,000 \text{ g}}{\text{kg}}$$

where  $A = \frac{\text{pCi Lead-210 measured}}{\text{kg GAC (dry weight)}}$

#### II. Calculation of theoretical Lead-210 accumulated on the GAC.

##### Assumptions:

- (i) All radon-222 removed by the GAC was completely retained.
- (ii) All lead-210 accumulation originates from decay of the radon-222 progeny. Any direct adsorption of lead-210 from the water supply or lead-210 resulting from the decay of other adsorbed species such as radium-226 was considered negligible.
- (iii) The measured water flowrate and radon removed by a given volume of GAC were constant over a sampling interval.



- A. Calculation of pCi of Radon-222 adsorbed in a given volume of GAC during the entire operating period (up to time of coring)

$$A_{iRn} = Q_{wi} (C_{inf_i} - C_{eff_i}) t_i$$

where  $A_{iRn}$  = pCi radon adsorbed during sampling interval i

$Q_{wi}$  = water flowrate during sampling interval i (L/d)

$C_{inf_i}$  = measured influent radon into volume of GAC during sampling period i (pCi/L)

$C_{eff_i}$  = measured effluent radon out of volume of GAC during sampling period i (pCi/L)

$(C_{inf_i} - C_{eff_i})$  = net change in radon activity through the volume of GAC (pCi/L)

$t_i$  = length of time of sampling interval (d)

$$A_{TRn} = \sum_{i=1}^n A_{iRn}$$

where  $A_{TRn}$  = pCi of radon adsorbed to a given volume of GAC during the entire operating period (up to time of coring)

- B. Calculation of mass of Radon-222 adsorbed to a given volume of GAC

$$M_{Rn} = A_{TRn} \times \frac{6.50 \times 10^{-18} \text{ g Rn}}{\text{pCi Rn}}$$

where  $M_{Rn}$  = g of radon adsorbed to a given volume of GAC during the operating period (up to the time of coring)

$$\frac{6.50 \times 10^{-18} \text{ g Rn}}{\text{pCi Rn}} = \frac{2.22 \text{ dpm}}{1 \text{ pCi}} \times \frac{1}{\lambda_{Rn}} \times \frac{\text{mole Rn}}{6.023 \times 10^{23} \text{ atoms}} \times \frac{222 \text{ g Rn}}{\text{mole Rn}}$$

$$\lambda_{Rn} = \frac{\ln 2}{t_{1/2_{Rn}}} = \frac{0.693}{(3.82 \text{ d})(24 \text{ hr/d})(60 \text{ min/hr})} = 1.26 \times 10^{-4} \text{ min}^{-1}$$

where  $\lambda_{Rn}$  = number of radon atoms disintegrating per total radon atoms present per minute

$t_{1/2_{Rn}}$  = half-life of Radon-222 = 3.82d

- C. Calculation of atoms of Radon-222 adsorbed to a given volume of GAC.

$$N_{Rn} = M_{Rn} \times \frac{\text{mole Rn}}{222\text{gRn}} \times \frac{6.023 \times 10^{23} \text{ atoms Rn}}{\text{mole Rn}}$$

where  $N_{Rn}$  = number of atoms of radon adsorbed to a given volume of GAC

- D. Calculation of mass of Lead-210 (Pb) adsorbed to a given volume of GAC

$$N_{Pb} = N_{Rn}$$

where  $N_{Pb}$  = number of atoms of Lead-210 adsorbed to a given volume of GAC

$$M_{Pb} = N_{Pb} \times \frac{\text{mole Pb}}{6.023 \times 10^{23} \text{ atoms}} \times \frac{210\text{g Pb}}{\text{mole Pb}}$$

where  $M_{Pb}$  = g of Lead-210 adsorbed to a given volume of GAC

- E. Calculation of pCi of Lead-210 (Pb) adsorbed to a given volume of GAC

$$A_{T_{Pb}} = M_{Pb} \times \frac{\text{pCi Pb}}{1.24 \times 10^{-14} \text{ g Pb}}$$

$$\frac{\text{pCi Pb}}{1.24 \times 10^{-14} \text{ g Pb}} = \frac{\text{pCi}}{2.22 \text{ dpm}} \times \lambda_{Pb} \times \frac{6.023 \times 10^{23} \text{ atoms Pb}}{\text{mole Pb}} \times \frac{\text{mole Pb}}{210\text{g Pb}}$$

where  $A_{T_{Pb}}$  = pCi Lead-210 adsorbed to a given volume of GAC

$$\lambda_{Pb} = \frac{\ln 2}{t_{1/2_{Pb}}} = \frac{0.693}{(21\text{yr})\left(\frac{365\text{d}}{\text{yr}}\right)\left(\frac{24\text{hr}}{\text{d}}\right)\left(\frac{60\text{min}}{\text{hr}}\right)} = 6.28 \times 10^{-8} \text{ min}^{-1}$$

where  $\lambda_{Pb}$  = number of lead-210 atoms disintegrating per total lead-210 atoms disintegrating per total Pb atoms present per minute

$$t_{1/2_{Pb}} = \text{half-life of Lead-210} = 21 \text{ yr}$$

- F. Calculation of pCi of Lead-210 per mass of GAC:

$$\frac{\text{pCi Lead-210}}{\text{kg}} = \frac{A_{T_{Pb}}}{x}$$

where  $x$  = kg (dry weight) of GAC per given volume

**TECHNICAL REPORT DATA**  
(Please read instructions on the reverse before completing)

1. REPORT NO.		2.		3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE RADON REMOVAL USING POINT-OF-ENTRY WATER TREATMENT TECHNIQUES				5. REPORT DATE	
				6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) Nancy E. Kinner, James P. Malley, Jr. and Johnathan A. Clement				8. PERFORMING ORGANIZATION REPORT NO. BNC1A	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Research Group University of New Hampshire Durham, New Hampshire				10. PROGRAM ELEMENT NO. CR812602	
				11. CONTRACT/GRANT NO. Final 10/88-6/90	
12. SPONSORING AGENCY NAME AND ADDRESS Risk Reduction Engineering Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268				13. TYPE OF REPORT AND PERIOD COVERED	
				14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES Project Officer: Kim R. Fox (513) 569-7820					
16. ABSTRACT <p>The purpose of this EPA Cooperative Agreement was to evaluate the performance of POE granular activated carbon (GAC), and diffused bubble and bubble plate aeration systems treating a ground water supply containing radon (<math>35,620 \pm 6,717</math> pCi/L. The pattern of loading to the units was designed to simulate daily demand in a household. Each of the systems was evaluated with respect to three primary factors: radon removal efficiency, potential problems, and economics.</p> <p>The radon removal efficiencies of the POE GAC units gradually deteriorated over time from 99.7% to 79% for the GAC without pretreatment and 99.7% to 85% for the units preceded by ion exchange. It appeared that iron sorption caused fouling of the GAC surface or caused channeling of water through the bed. The gamma emissions data indicated that the zone of radon removal slowly moved down the GAC bed. At higher radon loadings, the GAC units may not be able to dampen variations in influenc activity and flow without some increase in effluent activity.</p> <p>The bubble plate and diffused bubble POE units were very efficient ( 99%) at removing radon from the water. This resilience is primarily due to the high air to water ratios supplied by the aeration blowers. One major problem associated with the aeration techniques is iron oxidation/precipitation. Iron treatment will be required in most all POE applications which use aeration.</p>					
17. KEY WORDS AND DOCUMENT ANALYSIS					
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS		c. COSATI Field/Group	
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC		19. SECURITY CLASS (This Report) UNCLASSIFIED		21. NO. OF PAGES	
		20. SECURITY CLASS (This page) UNCLASSIFIED		22. PRICE	