

Figure 15. Combined Chlorine Removal Versus Rated Capacity for Eight Point-of-Use GAC Filters (Adams and Randtke, 1992c).



Figure 16. Removal of Atrazine and Hydroxydeisopropylatrazine (OEAT) by a Strong-Acid Cation Exchange Resin (Witt and Randtke, 1992).

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These results suggest that conventional ion-exchange softening is expected to be effective for removing atrazine and its degradation products only if the resins are regenerated prior to the initial breakthrough of calcium.

## Ozonation

In a pilot-plant study conducted for the Lincoln Water System in Nebraska, Hulsey *et al.* (1993) found that an ozone dosage of only 3 mg/L was able to remove more than 80 percent of the atrazine spiked into the water at a concentration of about 5.5  $\mu$ g/L. However, under these conditions, more than 1  $\mu$ g/L of deethylatrazine and a measurable amount of deisopropylatrazine were detected the finished water; and the presence of other atrazine degradation products could not be ruled out. This study led to a more indepth study of the ozonation of atrazine.

As reported by Adams and Randtke (1991, 1992a, & 1992b), the reaction of atrazine with ozone was found to be first order with respect to both atrazine and ozone and dependent on pH, alkalinity, and temperature. A model employing rate constants based on laboratory data was developed and was shown to predict the destruction of atrazine reasonably well for waters having a relatively low ozone demand. The rate of reaction of ozone with several atrazine degradation products was quantified; the degradation pathways were explored; and hydrogen peroxide was found to strongly catalyze the oxidation of atrazine by ozone.

Dosages of ozone typically employed in practice produce little or no ringcleavage, and there is no reason to believe that uncleaved by-products are less toxic to humans than atrazine itself. Very high dosages might produce some cleavage of the triazine ring, but such dosages would be unreasonably expensive and there is no guarantee that the cleaved by-products are entirely non-toxic. Various studies have demonstrated the ability of various advanced oxidation processes (typically involving the use of ozone in combination with peroxide or UV light) to oxidize atrazine; but these processes also produced both cleaved and uncleaved degradation products. Hence, it is illogical to use ozone or other oxidative processes to remove atrazine except where they are already in use for other purposes. Adsorptive processes, if effective and affordable, are a much more logical choice, since physical removal is expected to result in little or no by-product formation (although some by-product formation may occur as a result of surface catalysis or biological transformations).

## Membrane Processes

Reverse osmosis membranes are able to remove most small (i.e., low molecular weight, MW) molecules, including atrazine and many other synthetic chemicals, from solution. The degree of removal will depend on the type of membrane used (e.g., Fronk and Baker, 1990; Duranceau *et al.*, 1992). Removal may also depend on such factors as ionic strength, hardness, and the nature and amount of the natural organic matter present in the water (Devitt *et al.*, 1994). Ultrafiltration and nanofiltration membranes having

low-MW cut-off points should achieve at least partial removal of atrazine; but "looser" membranes having high-MW cut-off points are generally expected to accomplish little or no removal of atrazine unless used in conjunction with an adsorbent such as PAC (e.g., Clair *et al.*, 1996). Pilot tests should be conducted using the *in-situ* water to verify the capability of a particular membrane to remove the compounds of interest.

# Conclusions

- The current MCL for atrazine includes a very large safety factor but does not directly address atrazine's degradation products. As a result of the on-going efforts of various parties, including a special review being conducted by the U.S. EPA, the MCL may eventually be revised upward or downward.
- 2) Atrazine is frequently present in surface water supplies in the midwestern U.S., sometimes at concentrations exceeding 3  $\mu$ g/L. The highest concentrations typically occur in spring and summer runoff following application. Concentrations in streams and rivers tend to be much more variable than those in lakes and reservoirs; but elevated levels tend to persist for longer periods of time in lakes and reservoirs.
- 3) Certain atrazine degradation products are often present in surface water supplies in the midwestern U.S., but they are found at concentrations lower and less variable than those of the parent compound. In ground water supplies, the absolute concentrations of atrazine and its degradation products are generally lower than in surface water supplies, but the degradation products tend to represent a relatively greater fraction of the total residue.
- 4) Both voluntary and mandatory efforts are being made to control the amount of atrazine entering surface and ground water supplies. There is disagreement over the effectiveness of these measures, and it appears that long-term studies will be needed to resolve the issue.
- 5) As of December, 1995, there were no public water supply systems in U.S. EPA Region VII deemed to be out of compliance with the current MCL.
- 6) Most conventional treatment processes, including coagulation, softening, and filtration, as well as oxidation with chlorine, chlorine dioxide, or potassium permanganate, do not achieve substantial removal or alteration of either atrazine or its degradation products.
- PAC adsorption can achieve substantial removal of atrazine and related contaminants from drinking water and presently appears to be the best treatment option in most cases.

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- 8) PAC can be effective when added before or after lime or metal-salt coagulants, but simultaneous addition is likely to impair its performance. Process performance can be adversely affected by inadequate mixing and contact time. The suspendability of the PAC may play an important role in process performance, especially where little or no mixing is provided.
- 9) GAC can effectively remove atrazine and its degradation products from drinking water. Only partial removal is achieved for designs typically used for taste and odor control; but complete removal can be achieved using a sufficient contact time.
- 10) Atrazine can be partially metabolized to deethylatrazine on GAC columns, but this provides no obvious benefit from a human health standpoint.
- 11) Point-of-use GAC filters can effectively remove atrazine and its degradation products from tap water throughout their stated life if they are properly designed and contain a sufficient amount of GAC. Partial removal can be accomplished using point-of-use GAC filters containing smaller amounts of GAC. Removal of atrazine has been found to correlate reasonably well with removal of residual chlorine.
- 12) Atrazine and its degradation products can be adsorbed by a strong-acid cation exchange resin, but they have been found to be chromatographically displaced by calcium.
- 13) Modest dosages of ozone can effectively reduce atrazine concentrations to below the MCL, as can various advanced oxidation process; but the various atrazine degradation products thereby formed are not physically removed from the water and may be no less harmful to human health.
- 14) Atrazine can be effectively removed by reverse osmosis membranes and by some nanofiltration and ultrafiltration membranes; but pilot studies should be conducted on the specific water to be treated to verify the performance of a particular type of membrane. Removal of atrazine can also be accomplished by using PAC in combination with ultrafiltration and microfiltration membranes.
- 15) Given the current level of uncertainty that exists in regard to the MCL for atrazine as well as various other contaminants in drinking water, water utilities should exercise a great deal of caution before making any large capital investment in treatment related facilities.

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#### Radon Removal Technologies for Small Communities

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## Introduction

Radon is an inert gas found naturally in soil and rock formations and, due to its volatility, can be transferred into the atmosphere, buildings, and groundwater supplies. It is one of the contaminants that the U.S. Environmental Protection Agency (USEPA) is required to regulate under the Safe Drinking Water Act (SDWA). Groundwater radon concentrations range from less than 100 pCi/L to greater than 1,000,000 pCi/L (Longtin 1990) and depend on geology, with high radon concentrations associated with granitic formations. Technologies for radon removal from groundwater are currently limited to aeration and liquid phase granular activated carbon (GAC). Compliance with the final radon regulation is expected to impact a large number of utilities using groundwater sources. Small communities (populations  $\leq$  10,000) are expected to bear the major impacts of this rule. This burden may be particularly great for very small public water systems (populations  $\leq$  500 people) using groundwater without treatment facilities installed.

## Anticipated Rule

The 1996 SDWA amendments required USEPA to withdraw the proposed maximum contaminant level (MCL) of 300 picocurie per liter (pCi/L) and to promulgate a final radon drinking regulation by August 2000. USEPA is expected to

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repropose a radon regulation in August 1999, with an MCL to be based on a health risk reduction and cost analysis that takes costs and benefits of control programs from other sources into account. The MCL is expected to be near 300 pCi/L. USEPA is also expected to propose an Alternative MCL set at a level that would result in a contribution of radon from drinking water to indoor air equivalent to the national average concentration of radon in outdoor air. A National Academy of Sciences study (NAS 1998) determined a value of 4,000 pCi/L for the Alternative MCL. The 1996 SDWA amendments require USEPA to set an Alternative MCL because the risk-based MCL is more stringent. A local or State radon multimedia mitigation program must be in place in order for a water supplier to comply with the Alternative MCL. Thus, water suppliers must be cognizant of all sources of radon that may potentially impact their customers.

## **Potential Impacts**

USEPA (1999) issued a "Health Risk Reduction and Cost Analysis for Radon in Drinking Water" that provides estimates of the costs and benefits for potential MCLs between 100 pCi/L and 4,000 pCi/L (the anticipated Alternative MCL). Table 1 provides a summary of the number of Community Water Systems (CWSs) impacted by potential MCLs of 100 pCi/L, 300 pCi/L, and 4,000 pCi/L, showing the associated costs and benefits for very small systems (populations  $\leq$  500), small systems (population  $\leq$  10,000), and total systems (all population sizes). Note that throughout this range of potential MCLs, the estimated costs are in all cases greater than the estimated benefits.For an MCL of 300 pCi/L, USEPA estimates that 16,657 CWSs would be impacted, with annual costs of \$373 million per year (\$M/yr) and annual benefits of \$343 M/yr. The 16,251 small systems impacted represent over 97 percent of the total systems affected, and would bear 76 percent of the costs but receive only 38 percent of the benefits. The 12,535 very small systems represent 75 percent of the systems affected, and would bear 42 percent of the costs while receiving less than 6 percent of the benefits.

#### Implementation Issues

Besides economic concerns, utilities may encounter technical difficulties and environmental issues when implementing treatment technologies, which are currently limited to aeration and liquid phase GAC. These problems can be better understood by examining radon occurrence and fate, as illustrated by Figure 1. Radon-222, the isotope of interest, is a member of the uranium decay series, which is produced in groundwater by the decay of radium-226 in aquifer materials. Radon itself decays (half-life of 3.8 days) through several short-lived progeny (half-lives all less than 30 minutes) to lead-210 (half-life of 19.4 years). In radon removal systems, radon and its short-lived progeny are either released to the atmosphere via aeration or are adsorbed on granular activated carbon. The alpha radiation from radon and its short-lived progeny constitute the major health risk due to inhalation. In addition, the short-lived progeny adsorbed on the GAC emit beta-gamma radiation that may pose concerns about operator exposure during GAC