Design and Operation of Point-of-Use Treatment System for Arsenic Removal

Bruce M. Thomson, M.ASCE\textsuperscript{1}; T. Jeffrey Cotter\textsuperscript{2}; and Joseph D. Chwirka\textsuperscript{3}

Abstract: A point-of-use (POU) system was designed and constructed using commercially available activated alumina to remove arsenic from drinking water. Testing with City of Albuquerque chlorinated tap water containing an average of 23 \textmu g/L arsenic found that 1 L of adsorbent would provide water for direct consumption by a family of four for 435 days. It was estimated that the POU system constructed for this study could be sold for $162, and the arsenic adsorption columns were estimated to cost $4. A monthly cost to the customer of $10/month was estimated to purchase, install, and operate this POU system, assuming annual replacement of adsorption media cartridges. The implications of relying upon POU systems to comply with a new drinking water standard for arsenic are discussed.

DOI: 10.1061/(ASCE)0733-9372(2003)129:6(561)

CE Database subject headings: Arsenic; Abatement and removal; Potable water; Water treatment.

Introduction

The Safe Drinking Water Act Amendments of 1996 mandated that USEPA develop and promulgate a new maximum contaminant level (MCL) for arsenic by 2001 [42 USC 300g-1 (b)] as a result of concerns that the existing standard of 50 \textmu g/L did not provide adequate protection of the public. A final MCL of 10 \textmu g/L was published in January 2001 (USEPA 2001).

A new drinking water standard for arsenic will inordinately impact water utilities which rely upon groundwater because these systems generally do not provide any water treatment beyond simple chlorination (and sometimes fluoridation). Thus, the need to treat arsenic will require construction and operation of new treatment facilities which would be costly and will create new and unfamiliar infrastructure for the utility to manage.

Two investigations have found that the costs of compliance with the new arsenic standard will result in monthly costs ranging from a few dollars per month for customers of large water systems with only a few wells impacted by high As levels, to approximately $100/month for customers of very small water systems in which their only well requires treatment (Bitner et al. 2001; Gurian et al. 2001).

An alternative to centralized water treatment for As removal is point-of-use (POU) treatment systems. These are small units installed at the customer’s tap. The advantage of POU systems is that they only treat water intended for human consumption or household use. POU systems are typically installed in the kitchen and provide a separate tap for the water used for drinking and food preparation. Examples of POU systems include home water softeners, under-the-sink water filters, and under-the-sink reverse osmosis systems. The objective of this study was to construct and test an under-the-sink POU system for As removal and to develop an estimate of the costs for its use in a small community.

Background

Previous investigations of As removal from groundwater have focused on four technologies (Clifford and Lin 1991; Amy et al. 2000; Chwirka et al. 2000): membrane processes; ion exchange; activated alumina adsorption; and iron hydroxide coagulation and microfiltration. Centralized reverse osmosis is not suitable for small utilities because it is too expensive and complicated, and because it wastes too much water. Ion exchange and iron hydroxide coagulation/microfiltration are also problematic for small systems; IX because it has a very large salt requirement and associated brine disposal requirements, and iron hydroxide coagulation/ microfiltration because it is a complicated treatment process that small utilities cannot afford nor operate.

Clifford and Lin (1991) investigated As treatment options for San Ysidro, New Mexico and concluded that POU systems based on under-the-sink reverse osmosis (RO) units would be most effective for this small community. With financial assistance provided by the Environmental Protection Agency (EPA), RO systems were installed in every residence and commercial establishment in the community. These systems are still in use and this community is believed to be the only one in the United States which relies upon POU systems for As treatment. Thomson et al. (1995, 2000) evaluated the performance of these systems and found that, while they provide a high degree of As removal when they are regularly maintained, regular maintenance is difficult to achieve, thus the performance of the POU systems has
deteriorated with time. A further concern regarding under-the-sink RO systems is that they typically only recover 20–25% of the feed water and the rest is wasted to the sewer or septic tank. In communities located in arid climates this amount of waste is undesirable because of limited water resources.

An alternative to RO devices are systems which rely upon selective removal of As by adsorption onto metal oxide media such as activated alumina or ferric hydroxide. The advantages of this process are that it uses low-cost disposable cartridges that can be simply changed and it wastes no water. The objective of this study was to design, construct, and test an adsorption based POU system, determine its cost, and evaluate its potential for compliance with the new As standard.

**System Design and Testing**

The POU system designed for this project removes As by adsorption onto activated alumina. Alcan AA-FS50 media (Alcan Chemicals, Canada) was selected based on investigations using similar media for the City of Albuquerque (Clifford et al. 1998) and because it is approved for drinking water treatment by the NSF International 28×48 mesh size media was used. The principal variables which affect the performance of activated alumina are pH and empty bed contact time (EBCT). Because pH adjustment is not likely to be feasible in a small community, the testing in this study was done at ambient pH.

A flow diagram of the POU system designed for this test is presented in Fig. 1. Water is treated by passing it through a fiber wound cartridge prefilter, then a packed column of Alcan AA-FS50, and finally a third fiber wound sediment filter. The empty volume of the activated alumina filter was 1.0 L, hence a flow restrictor was added to reduce the flow through the AA column to 0.1 L/min, thereby providing an EBCT of 10 min. The flow restrictor was constructed by drilling a 0.4 mm hole in a polyethylene plug which was calculated to give a flow of 0.1 L/min at a pressure differential of 240 kPa (35 psig). A bladder storage tank was used to provide an acceptable delivery rate at the tap.

The POU system was constructed using components of a conventional under-the-sink water filter system (sold by Sears, Roebuck and Company of Hoffman Estates, Illinois). This system normally has two components, a sediment filter and an activated carbon column. The activated carbon was replaced with the activated alumina media, and a posttreatment filter column was added to assure that fines from the activated alumina media did not clog the flow restrictor.

**Arsenic Removal**

The results of the POU testing program are presented as a breakthrough curve in Fig. 2. They show that breakthrough ($C/C_0 = 0.1$) occurred after approximately 4,000 bed volumes and that exhaustion ($C/C_0 = 0.9$) occurred at approximately 10,000 bed volumes. Clifford et al. (1998) studied the effects of pH and...
EBCT on adsorption column run lengths for two different activated aluminas for Albuquerque groundwater. They found breakthrough at 20,000 bed volumes for water adjusted to pH 6.0, and approximately 1,000 bed volumes at a pH of 8.5 and a 10 min EBCT. The results of this study at pH 7.8 appear consistent with these results. The performance of a treatment system based on selective As adsorption is also dependent on other influential water quality characteristics, especially the presence of phosphate. Phosphate was not detectable in this water.

Note that this system used a conventional NSF International approved activated alumina media. There is much current research and development on new media such as granular ferric hydroxide (Driehaus et al. 1998) which may offer longer run lengths than achieved in this study. A further consideration is that this system was operated continuously at an EBCT of 10 min, and therefore treated approximately 140 L/days (38 gal/days). In normal household use the column would stand for many hours with no flow. Continuous operation of an adsorption system instead of intermittent operation thus represents a worst case scenario as the capacity of arsenic adsorbents increases when the media is allowed to stand. This is likely due to diffusion of arsenate into interior pores within the media, and development of polynuclear bonds between arsenate and the media with time (Fendorf et al. 1997). This will increase the capacity of the media and therefore the volume of water which could be treated before breakthrough occurred, however, the magnitude of this increase is not known.

Table 2. Estimated Retail Cost of Point-of-Use Arsenic Treatment System

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment filters (2)</td>
<td>$8</td>
</tr>
<tr>
<td>AA FS-50 Cartridge</td>
<td>$4</td>
</tr>
<tr>
<td>Filtration system with tap dispenser, flow restrictor, housing and all plumbing</td>
<td>$100</td>
</tr>
<tr>
<td>Bladder pressure tank</td>
<td>$50</td>
</tr>
<tr>
<td>Total cost</td>
<td>$162</td>
</tr>
</tbody>
</table>

The annual cost estimates for a single POU unit installed in a residence is presented in Table 3. For purposes of this calculation, it is assumed that a plumbing contractor would initially install the POU systems, after which they would be operated and maintained by the water utility as required by the Arsenic Rule (USEPA 2001). Installation costs principally consist of the labor to install the POU systems in each customer’s residence as there is no need for special tools or equipment. Based on the experience with the system used in this study, it is estimated that a typical installation will require 1 h. The pay for installers range from about $20/h (including benefits) for an employee of a small village in New Mexico to $50/h for an independent plumber. The life of a POU system is estimated at 5 years. The USEPA (2001) estimated a per capita direct water consumption rate of 2.3 L/day. Therefore, a family of four would have a daily consumption of 9.2 L/day (2.4 gal/day), and the expected life of a 1-L FS-50 activated alumina cartridge would be 435 days for this particular water. Annual replacement of the columns would provide a 20% margin of safety. The cost of compliance sampling ($8.25/year) is based on annual monitoring of a third of the units in a community (Gurian and Small 2002). More frequent monitoring requirements will increase the costs commensurately.

The annual costs for purchase of the POU systems and installation were calculated based on a 6% interest rate amortized over 5 years and rounded to the nearest dollar. The annual costs reflect a direct cost to the customer of about $10/month. It is approximately one-tenth the monthly cost of centralized treatment for small systems reported by Bitner et al. (2001).

Table 3. Estimated Annual Costs for Point-of-Use System Installed in Residence and Maintained by Water Utility

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
<th>Annual cost ($)/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point-of-use system cost (5 year expected life)</td>
<td>$162</td>
<td>$38/year</td>
</tr>
<tr>
<td>Installation cost (5 year expected life)</td>
<td>$50</td>
<td>$12</td>
</tr>
<tr>
<td>Sediment filter cartridges (4/year)</td>
<td>$16</td>
<td>$16</td>
</tr>
<tr>
<td>Activated alumina cartridges (1/year)</td>
<td>$4</td>
<td>$4</td>
</tr>
<tr>
<td>Village O&amp;M labor to replace cartridges</td>
<td>$20</td>
<td>$20</td>
</tr>
<tr>
<td>Compliance sampling and monitoring</td>
<td>$8</td>
<td>$8</td>
</tr>
<tr>
<td>Total annual costs</td>
<td>$108</td>
<td></td>
</tr>
</tbody>
</table>

Note: Annual costs for system purchase and installation are amortized over 5 years at an interest rate of 6%.

Discussion and Conclusions

This study demonstrated that a simple POU system based on conventional throw-away adsorption media can provide As treatment...
at an affordable cost. The homeowner was pleased with the taste of the treated water throughout the study. However, there are other considerations in evaluating whether this type of system is applicable to a small community. The first is performance of the system. The POU system tested in this study would provide over 1 year of treated water for direct consumption by a family of four, however, this performance is strongly dependent on the influent water quality characteristics. The principal factors affecting system performance are the type of media, pH, the major ion composition of the feed water, and the As concentration. While pH is the most important parameter affecting column performance, utilities which rely upon POU systems will almost certainly not be able to adjust solution pH as it is costly, relatively complicated, and will affect the corrosivity of the water. At present it is not possible to reliably predict the effect of influent water quality on the performance of adsorption systems. Until a better understanding of the effects of water quality on As adsorption is achieved, each utility considering POU systems should test candidate POU systems to confirm their performance using system water.

In order to utilize POU systems to achieve compliance with the Safe Drinking Water Act regulations, the water utility must own, operate, and maintain the POU systems (USEPA 2001). This means that the village operator must enter each residence to perform inspections, maintenance, and tap sampling. This is a difficult scheduling problem as many residents are not home during working hours. Further, some residents are reluctant to allow village employees into their homes due to personal conflicts which further complicates maintenance and sampling (Thomson et al. 1995, 2000). Utility operating of POU systems will be facilitated if maintenance is limited to simple annual replacement of disposable cartridges. Finally, POU and point-of-entry (POE) systems used in public water supply systems must be certified by the American National Standards Institute (ANSI) and NSF International. ANSI/NSF standard 53-2001 deals with POU/POE treatment devices.

A new drinking water standard for arsenic will be difficult to meet in small rural communities which rely upon groundwater as their source of supply because treatment will be costly and will require technical expertise that most of these communities cannot support. This study shows that POU systems may provide an affordable alternative to conventional water treatment, however, significant management and regulatory issues must be addressed. Furthermore, reliance upon POU systems represents a new paradigm in the U.S. water supply. Water utilities which use POU systems will, for the first time, be forced to acknowledge that their water is not safe to drink without further treatment. Selection of POU treatment to achieve compliance should therefore be given full and open public discussion.

References


