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Pilot Demonstrations of Arsenic Treatment Technologies in U.S. Department of Energy Arsenic Water Technology Partnership Program

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Abstract

The Arsenic Water Technology Partnership program is a multi-year program funded by a congressional appropriation through the Department of Energy. The program is designed to move technologies from bench-scale tests to field demonstrations. It will enable water utilities, particularly those serving small, rural communities and Indian tribes, to implement the most cost-effective solutions to their arsenic treatment needs. As part of the Arsenic Water Technology Partnership program, Sandia National Laboratories is carrying out field demonstration testing of innovative technologies that have the potential to substantially reduce the costs associated with arsenic removal from drinking water. The scope for this work includes:

1. Selection of sites and identification of technologies for pilot demonstrations
2. Laboratory studies to develop rapid small-scale test methods
3. Pilot-scale studies at community sites involving side-by-side tests of innovative technologies

The goal of site selection is to identify sites that allow examination of treatment processes and systems under conditions that are relevant to different geochemical settings throughout the country. A number of candidate sites have been identified through reviews of groundwater quality databases, conference proceedings and discussions with state and local officials. These include sites in New Mexico, Arizona, Colorado, Oklahoma, Michigan, and California.

Candidate technologies for the pilot tests are being reviewed through vendor forums, proof-of-principle bench-scale studies managed by the American Water Works Association Research Foundation (AwwaRF) and the WERC design contest. The review considers as many potential technologies as possible and screens out unsuitable ones by considering data from past performance testing, expected costs, complexity of operation and maturity of the technology. The pilot test configurations will depend on the site-specific conditions such as access, power availability, waste disposal options and availability of permanent structures to house the test.

Conducting pilot tests for media comparison at all sites in need of arsenic treatment would be extremely time consuming and costly. Laboratory studies are being conducted using rapid small-scale column tests (RSSCTs) to predict the performance of pilot-scale adsorption columns. RSSCTs are a rapid and inexpensive method of investigating innovative technologies while varying water quality and/or system design. RSSCTs are scaled-down columns packed with smaller diameter adsorption media that receive higher hydraulic loading rates to significantly reduce the duration of experiments. Results for RSSCTs can be obtained in a matter of days to a few weeks, whereas pilot tests can take a number of months to over a year.

In the pilot tests, the innovative technologies will be evaluated in terms of adsorptive capacity for arsenic; robustness of performance with respect to water quality parameters including pH, TDS, foulants such as Fe, Mn, silica, and organics, and other metals and radionuclides; and potentially deleterious effects on the water system such as pipe corrosion from low pH levels, fluoride removal, and generation of disinfection by-products. The new arsenic MCL will result in modification of many rural water systems that otherwise would not require treatment. Simultaneous improvement of water quality in systems that will require treatment for other contaminants such as uranium, radon and radium would be an added benefit of this program.

Introduction

The Arsenic Water Technology Partnership (AWTP) program is a multi-year program funded by a congressional appropriation through the Department of Energy (DOE). The AWTP is a partnership between the American Water Works Association Research Foundation (AwwaRF), Sandia National Laboratories (SNL) and WERC (Waste-management Education & Research Consortium - A Consortium for Environmental Education and Technology Development Partners) and is designed to utilize the unique strengths of each member. The AwwaRF is managing a bench-scale research program, SNL is conducting pilot-scale demonstrations of treatment technologies, and WERC will evaluate the economic feasibility of the technologies investigated and conduct technology transfer activities.

The program is designed to move technologies from the bench-scale to demonstration and will enable water utilities, particularly those serving small rural communities and Indian tribes, to implement the most cost-effective solutions to their arsenic treatment needs. Depending on program funding, SNL will carry out side-by-side field testing of multiple innovative technologies at 10-15 sites throughout the United States (U.S.). Technologies that have the potential to substantially reduce the costs associated with arsenic removal from drinking water will be compared.

Although, no formal agreement is in place, other important partners in the program include the U.S. Environmental Protection Agency (EPA) and NSF International, Inc. The U.S. EPA is conducting demonstrations of individual treatment technologies at sites throughout the U.S. in order to obtain cost and performance data for full-scale systems. It is hoped that the information obtained from the SNL tests can be combined with the full-scale cost models from those tests to estimate full-scale costs for a large number of technologies at a given site. NSF International, Inc. is an independent non-governmental organization that develops consensus standards and certifies equipment and chemicals that are used in drinking water distribution systems. By working with NSF, the SNL testing program will be designed to collect information that technology vendors can use to accelerate certification of their technologies prior to use in public water systems. A significant proportion of the pilot demonstrations will be carried out in Native American communities. The assistance of the Navajo Nation Environmental Protection Agency (NNEPA) and the U.S. Indian Health Service will be essential for this work.

The scope for this program includes:

1. Selection of sites and identification of technologies for pilot demonstrations
2. Laboratory studies to develop rapid small-scale test methods
3. Pilot-scale studies at community sites involving side-by-side tests of innovative technologies

Figure 1 describes the flow of activities in the program. During the first year, major emphasis has been placed on site and technology evaluation, leading to development of criteria for selection of sites and technologies for the pilots. Initially, only commercially available technologies are being considered for the pilots; during subsequent years of the program, new technologies developed at universities and national laboratories will be included in the scope of the technology evaluation. Laboratory studies have included pre- and post-test characterization of adsorbent media and development of methods using rapid small-scale column tests (RSSCTs). Review of the results of a preliminary pilot test run on a well located near SNL (Khandaker et al. 2005) provided information useful for the design of subsequent pilots. A revised design was used for the first pilot (Socorro, New Mexico) as described below, and was reviewed by NSF International. Pilot testing of adsorbent media will likely take 9 to 12 months; other technologies such coagulation/filtration will be completed within weeks. The results of the tests will be used to support development of cost models by WERC.

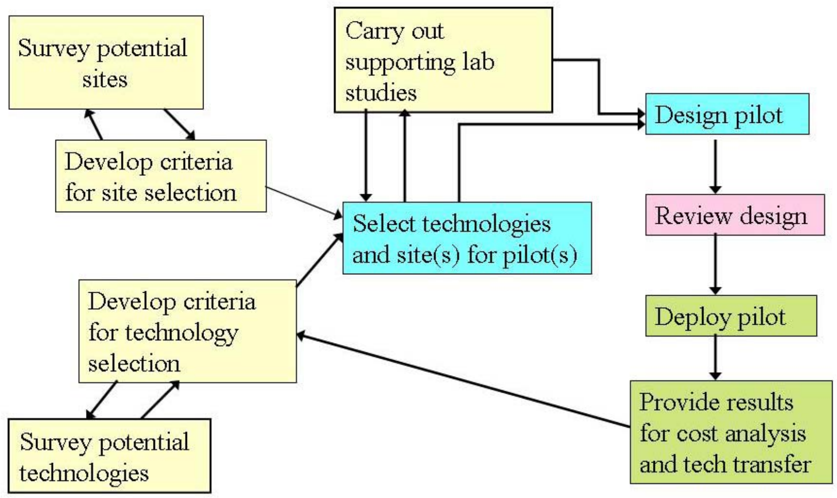


Figure 1. Flow diagram for activities in pilot demonstration program.

Site Selection

The goal of site selection is to identify sites that allow examination of treatment processes and systems under conditions that are relevant to different geochemical settings and socioeconomic conditions throughout the country. Naturally occurring arsenic is associated with a large number of different kinds of sources and exhibits a wide concentration range in groundwaters. Arsenic concentrations range from 1.1 µg/L to 6000 µg/L in the 7000 water samples collected in the Western U.S. and described in a study by Welch, Lico and Hughes (1988). Its association with other solutes that can affect the efficiency of the treatment process is also variable (Amy et al. 2004). These interfering solutes include silica, sulfate, vanadate, and phosphate. Arsenic is strongly enriched in silicic volcanics, derived volcanoclastic sediments and associated hydrothermal systems. Arsenic source rocks can also be enriched by potassium metasomatism, a low-temperature alteration process common in closed hydrographic basins in arid climates. In the eastern U.S., arsenic can be derived from sulfides in crystalline bedrock; in the Midwest, glacial deposits may provide the source of arsenic. In other areas, remobilization of arsenic previously sorbed onto the iron-oxide component of sediments is the major source. Figure 2 summarizes the arsenic levels in groundwater throughout the U.S. and potential sources at several locations (Welch et al. 2000; Ryker 2001).

The site selection criteria include both hydrochemical characteristics and sociological factors such as:

- Arsenic concentration >10 ppb
- Example of class of groundwater composition spanning ranges of
  - pH, TDS, concentrations of foulants such as Fe, Mn, silica, and organics
  - As(III)/As(V)
  - Concentrations of competing ions (VO_4^{3-}, SO_4^{2-}, etc.)
  - Presence of other metals and radionuclides of concern/benefit
- Small system size to be treated (< 10,000 users)
- Community support (water utility and municipal government), facilitating rapid deployment
- Ability to deal with residuals/treated effluent

A number of candidate sites have been identified through reviews of groundwater quality databases, conference proceedings and discussions with state and local officials. The initial pilot tests in the program will be conducted in New Mexico. Figure 3 identifies sites under evaluation. Additional sites are being identified in Arizona, Colorado, California, Oklahoma, and Michigan. Table 1 describes the chemistry of several sites under consideration for the first set of pilots. The current suite of pilot sites exhibits a considerable range on pH and concentrations of arsenic as well as potential foulants such as SiO_2. The last 2 columns in Table 1 describe the values of 90th and 10th percentiles of the distributions of solute concentrations for wells with arsenic concentrations greater than 20 ppb as tabulated in the National Water Information System (NWIS) (Amy et al. 2004).

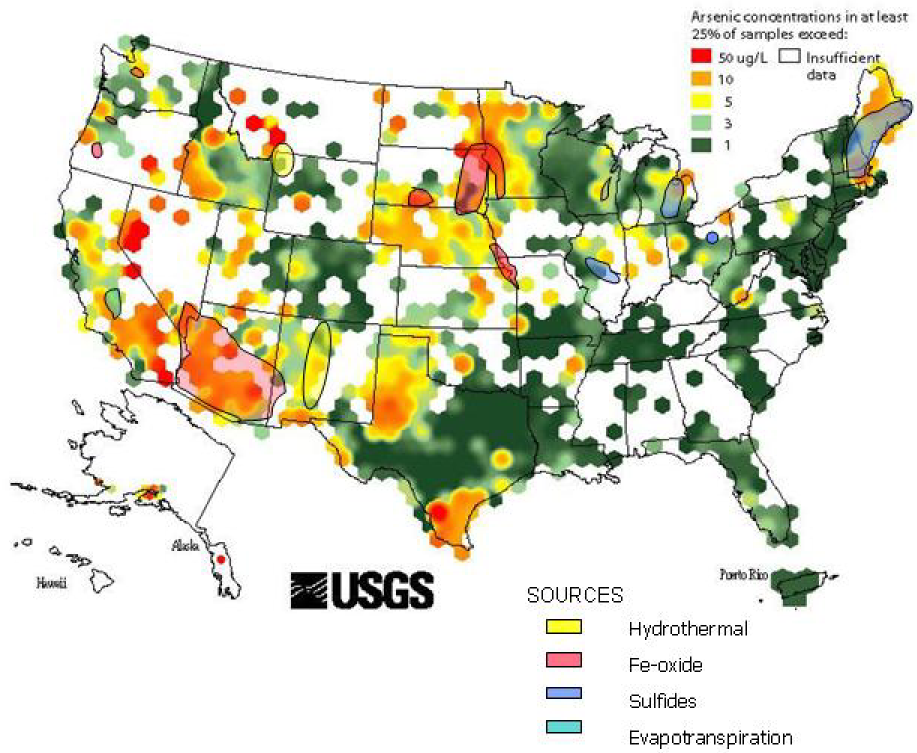


Figure 2. Distribution of arsenic concentrations in U.S. counties and potential sources of arsenic.

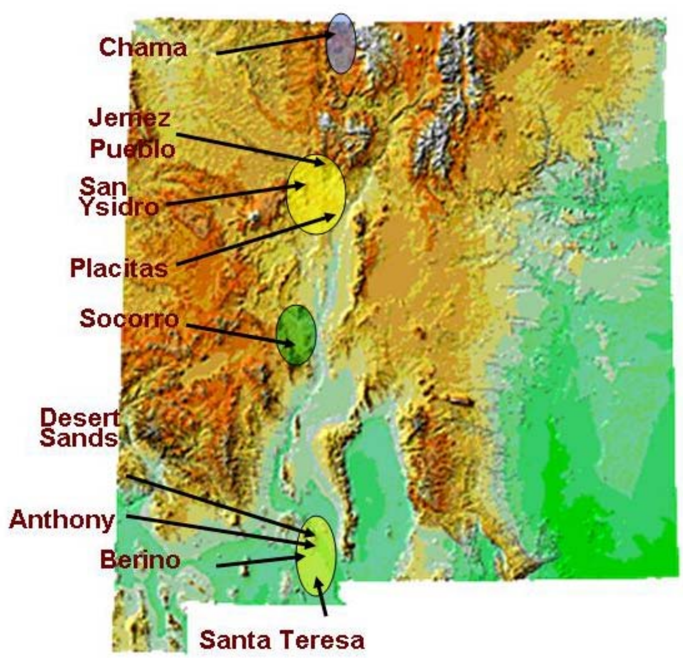


Figure 3. Candidates for pilot studies in New Mexico.

Table 1. Groundwater Compositions at Pilot Sites

Solute	KAFB, NM	Socorro NM	Jemez Pueblo NM	Desert Sands NM	Benton Tribe, CA	Chama NM	'High' As NWIS distribution	
							10 %	90%
As ppm	0.013	0.041	0.020	0.029	0.032	0.234	>0.02	>0.02
pH	8.1	7.7	8.1	7.6	9.4	7.43	6.8	8.4
F ppm	0.5	0.53	1.3	0.6	3.4	0.91	0.1	2.5
SiO_2 ppm	44	25	49	37.8	85	N/A	8	52
Fe ppm	N/A	0.001	0.7	0.04	0.38	4.92	0.05	7.8
Mn ppm	N/A	0.001	0.7	0.008	0.01	0.26	0.012	1.36
SO_4 ppm	30	30	40	170	47	227	5	0.517
Temp °F	77	92	N/A	80	N/A	N/A	37.6	69.1

Technology Evaluation

Candidate technologies for the pilot tests are being reviewed through vendor forums, proof-of-principle bench-scale studies managed by the AwwaRF and the WERC design contest. The review considers as many potential technologies as possible and screens out unsuitable ones by considering data from past performance testing, expected costs, complexity of operation and maturity of the technology.

For the past 2 years, SNL has organized Arsenic Treatment Technology Vendor Forums as part of the New Mexico Environmental Health Conference (see forum website at http://www.sandia.gov/water/arsenic.htm). At the forums, vendors of innovative technologies gave technical and marketing overviews of their products in a session open to all conference attendees. On the following day, the same company representatives were interviewed by teams of technical experts in closed sessions. The vendor technologies were graded by the interview teams on a number of attributes. This grading produced a ranking for the technologies at the forum. The technologies with highest ranks were considered for immediate pilot testing; other technologies were identified as promising but needing additional bench-scale verification. The results of the forum including vendor presentations and the evaluations can be found at the forum website link above.

Most of the treatment technologies being considered for pilots fall into two broad categories: 1) sorption processes that use fixed bed adsorbents and 2) membrane processes including coagulation/filtration with or without electrochemical processes. Several innovations that could lead to lower treatment costs have been proposed for adsorptive media systems. These include: 1) higher capacity and selectivity using mixed oxides composed of iron and other transition metals, titanium and zirconium based oxides, or mixed resin-metal oxides composite media; 2) improved durability of virgin media and greater chemical stability of the spent media; and 3) use of inexpensive natural or recycled materials with a coating that has a high affinity for arsenic. Improvements to filtration-based treatment systems include: 1) enhanced coagulation using improved iron compounds, polyelectrolytes, and electrical gradient or via electrochemical reactions and 2) improved filtration with nanocomposite materials.

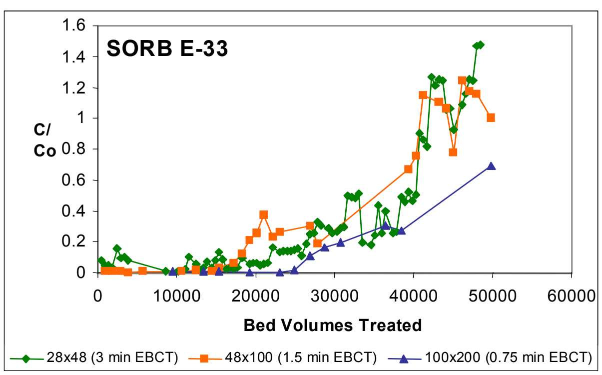
Laboratory Studies: Rapid Small-Scale Column Tests (RSSCT)

Conducting pilot tests for media comparison at all sites in need of arsenic treatment would be extremely time consuming and costly. Laboratory studies are being conducted using rapid small-scale column tests (RSSCTs) to predict the performance of pilot-scale adsorption columns. RSSCTs are a rapid and inexpensive method of thoroughly investigating innovative technologies while varying water quality and/or system design. RSSCTs are scaled-down columns packed with smaller diameter adsorption media that receive higher hydraulic loading rates to significantly reduce the duration of experiments. Results for RSSCTs can be obtained in a matter of days to a few weeks, whereas pilot tests can take a number of months to over a year.

This method uses adsorption theory to develop scaling relationships that allow correlation of lab-scale column results operated at accelerated flow rates to full-scale column performance. The RSSCT concept is based upon a theoretical analysis of the adsorption processes that govern performance including solution and surface mass transport and adsorption kinetics. Mass transfer models have been used to determine dimensionless parameters that establish similitude between the small- and large-scale columns. The performance of small columns media can then be scaled up to predict performance and aid in the design of a full-scale treatment operation.

If perfect similitude is maintained, the small columns, using small diameter media in the RSSCT procedure, will have breakthrough profiles that are directly proportional to full-scale columns (Crittenden et al. 1986). Two mass transfer models are most frequently used to model adsorption columns, the dispersed flow pore and surface diffusion model (DFPSDM) and the homogeneous surface diffusion model (HSDM). The most general model, the DFPSDM, includes pore diffusion and surface diffusion, as well as axial dispersion. This model includes many of the known transport and kinetic phenomena that occur in fixed bed adsorbents; therefore, a dimensional analysis allows the development of scaling factors. The HSDM models surface diffusion while neglecting pore diffusion and axial dispersion. It has been shown that surface diffusion is much greater than pore diffusion for strongly adsorbed species (Hand 1983); therefore, the contribution of pore diffusion to the adsorbate transport has been neglected. A more detailed discussion of the RSSCT scaling equations can be found in Appendix A to this paper.

Breakthrough curves from previous studies using iron oxide adsorption media and Albuquerque tap water are shown in Figure 4. These particular columns were designed using the proportional diffusivity scaling equations. Similarity in breakthrough curves is apparent between the different size columns.



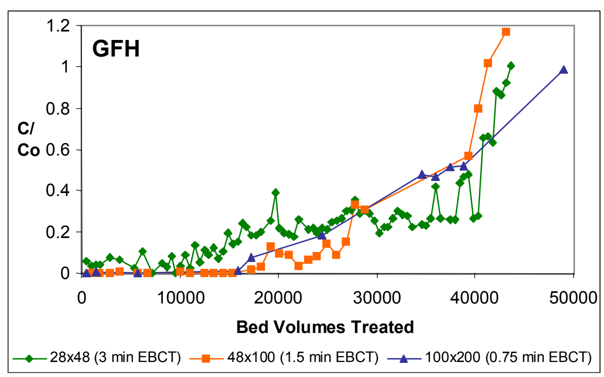


Figure 4. Arsenic breakthrough curves for Albuquerque tap water onto iron oxide adsorption media (Aragon 2004).

Similar breakthrough relationships are expected from the future pilot columns and their respective RSSCTs. The use of the RSSCT methodology to support the pilot test in Socorro, NM is described below.

Pilot Demonstrations Overview

Pilot-scale testing provides a cost effective method to optimize a water treatment methodology prior to full-scale implementation. The final water treatment system can be modeled and tested using a pilot-scale demonstration that considers the communities long-term needs. More specifically, a pilot-scale system is used to vary design process parameters (such as contact time, filtration rate, or mixing energy) and treatment materials (filter media, new chemicals, or chemical doses) to provide the information necessary for the full-scale design. This information or performance criteria include the following areas:

1. Performance, as measured by arsenic removal
2. Costs, including capital and Operation and Maintenance (O&M) costs
3. O&M requirements, including personnel requirements, and level of operator training
4. Waste residuals generation

In the pilot tests, the innovative technologies will be evaluated in terms of adsorptive capacity for arsenic; robustness of performance with respect to water quality parameters including pH, TDS, foulants such as Fe, Mn, silica, and organics, and other metals and radionuclides; and potentially deleterious effects on the water system such as pipe corrosion from low pH levels, fluoride removal, and generation of disinfection by-products. The pilot test configurations will depend on the site-specific conditions such as access, power availability, waste disposal options and availability of permanent structures to house the test. The pilot demonstration will have three participants with specific roles and responsibilities: SNL, the technology provider (vendor), and the site owner. SNL is providing funding for the demonstration including equipment, materials and labor, preparing designs and a sampling plan/protocol including all chemical analyses to be performed on site; fabricating and installing equipment in the pilot facility, and documenting the results. In addition, characterization of the media by a variety of chemical techniques and small-scale column tests is being carried out by SNL in order to optimize the interpretation of the pilot test results. Vendor participation in design, start-up, optimization, and operational evaluation of their respective product is being encouraged and depends on the policies of the particular company. Vendors have provided material and/or equipment (in some cases at no charge) and Material Safety and Data Sheets for their adsorbent media. The host community will provide assistance with on-site logistics, daily operation and maintenance, and sample collection. In addition, the utility is providing water, electricity, and site security.

Pilot Demonstration in Socorro, New Mexico

The New Mexico Environment Department has identified over 90 public water systems that currently exceed the 10 ppb MCL for arsenic. Socorro Springs in Socorro, New Mexico was selected for the first demonstration site. The pilot test, which compares five innovative technologies, began in the winter of 2004 and should last about nine months. These treatment processes were chosen from more than 20 candidate technologies that were reviewed by teams of technical experts at Arsenic Treatment Technology Vendor Forums organized by SNL and held at the 2003 and 2004 New Mexico Environmental Health Conferences. All of the technologies use adsorbent media in a fixed bed to remove arsenic. Table 2 describes the five media that are being tested:

Table 2. Adsorbent Media Evaluated in Socorro Springs Test

Company	Technology Name	Adsorbent
MEI	Isolux 302M	Zirconium Oxide
Hydroglobe	MetSorbG	Titanium Oxide
AdEdge	AD33	Ferric Oxide
Engelhard	ARM200	Ferric Oxide
Purolite	ArsenX^{np}	Hybrid resin

Rapid Small-Scale Column Tests

RSSCTs are being conducted in support of the Socorro, NM Pilot Demonstration Project. RSSCTs were scaled down from pilot scale and designed using both proportional diffusivity and constant diffusivity scaling equations. Design parameters for both the pilot scale and small scale are shown in Table 3.

Table 3. Correspondence of Design Parameters for Pilot-Scale and Small-Scale Column Studies for Socorro, NM

Parameter	Pilot Scale	RSSCT	Units
Column Diameter	7.6 (3)	1.0 (0.4)	cm (in)
Particle Diameter	0.25-2.0	0.15-0.18	mm
EBCT	2-5	0.05-0.9	min
Bed Height	50-130 (20-50)	8-30 (3-12)	cm (in)
Flow Rate	1100-1900 (0.3-0.5)	20-120 (0.005-0.03)	ml/min (gpm)
Hydraulic Loading Rate	24-32 (6-8)	15-125 (3-32)	cm/min (gpm/ft^2)
Duration	6-12 months	2-36 days	--

Socorro Pilot System Design

The objectives of the Socorro Pilot include evaluation of:

1. the treatment performance of five adsorptive media using the same water source;
2. the effects of pH adjustment and contact time on the performance of selected media; and
3. limited assessment of maintenance and operational requirements for all media.

The treatment performance will measure the arsenic removal capacity of all five media under ambient pH conditions (approximately 7.7). Simultaneously, additional columns using the Isolux 302M, Metsorb, and AD33 media will be evaluated at an adjusted pH of 6.8 to determine the effect on arsenic removal capacity as a function of pH. The pH will be lowered using a CO_2 injection system, which does not require the use of mineral acids. A second parameter, empty bed contact time (EBCT), will be varied for the AD33 media to determine the correlation between treatment contact time and arsenic removal. The results of this last test will help design future, potentially shorter, pilot tests.

The pilot-scale columns were designed based on full-scale design parameters to minimize scaling effects, thereby improving confidence in the results. It is understood that pilot-scale columns are sub-optimal for representation of full-scale maintenance and operational requirements; however, efforts will be directed at collection of some operational parameters. These include the pressure drop across the media and the corresponding backwash requirements (frequency and volume), as well as the adsorptive capacity of media to breakthrough (defined as 8 ppb). In addition, media handling characteristics and the potential corrosivity and scale formation by effluent water from each of the media will be evaluated through the use of corrosion coupons and saturation index calculations.

Pilot-scale operational parameters for each media are based upon full-scale operating conditions as provided by the respective vendors. Table 4 provides a summary of the basis for design of the pilot columns for all five media.

Table 4. Summary of Design Basis for Socorro Springs Pilot

Criteria	MEDIA									
	MetSorb		AD33				Isolux 302M		ARM 200	ArsenX^{np}
Number of Pilot Scale Columns	2		4				2		1	1
Hydraulic Loading Rate (HLR), gpm/ft^2	8		6				23		6	8.1487
Empty Bed Contact Time (EBCT), min.	2	2	2	4	5	4	0.5	0.5	4	3
Pre-filtration requirements	No	No	No	No	No	No	Yes (0.5um)	Yes (0.5um)	No	No
Influent pH	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Adjusted pH		6.8				6.8		6.8		
pH adjustment chemical and dose		< 0.5 lbs. CO_2				< 0.5 lbs. CO_2		< 0.5 lbs. CO_2		
Column Height (Hc), inches	39	39	39	60	60	60	10	10	60	60
Column Diameter (D), inches	3	3	3	3	3	3	1	1	3	3
Media Depth (Hm), inches	25.7	25.7	19.3	38.5	48.12	38.5	10	10	38.5	39.2
Media Volume (V), liters	2.97	2.97	2.23	4.46	5.57	4.46	0.48	0.48	4.46	4.74
Water Flowrate (Q), gpm	0.4	0.4	0.3	0.3	0.3	0.3	0.5	0.5	0.3	0.4
Face Velocity (v), ft/s	0.018		0.013				0.20		0.013	0.018
Backwash Flowrate (Q_{BW}), gpm	0.3		0.3				N/A		0.3	0.2

Construction of Pilot and Planned Operation

The pilot equipment was pre-fabricated at SNL prior to delivery to the Socorro Springs field site. The pilot test columns were installed inside the Socorro site chlorination building (Figure 5). All columns will be operated simultaneously in a down flow configuration at low pressures (~15 psi). Influent water will be chlorinated, and flow rates will range from 0.3 to 0.5 gallons per minute (gpm). Hydraulic loading rates, water flow rates and face velocities will remain constant during the testing. EBCTs and the corresponding volume of media in each column vary per design and shall remain fixed throughout the pilot testing. Treated effluent from the tests will be discharged on site via surface release into a subterranean infiltration gallery; none of the treated water will be returned to the drinking water distribution system. Spent media will be returned to SNL for evaluation and disposal.

Treated water will be sampled daily the first two weeks during the system integrity verification phase and then weekly for the remainder of the test period. If the adsorbent media perform as expected, no arsenic should be detected in the treated water for at least 4 to 6 months. (The lower limit of detection for arsenic using the Inductively Coupled-Mass Spectrometer at SNL is less that 1 ppb.) Eventually, as the adsorbent capacity of an adsorbent medium is exhausted, detectable amounts of arsenic will appear in the treated water. The concentration of arsenic will gradually increase, and when the capacity of the medium is completely exhausted, the arsenic concentrations in the untreated and treated water will be the same. In some cases, testing will stopped before this happens (i.e., when the arsenic concentration in the treated water is about 8 μg/L).

Figure 5. SNL Pilot Arsenic Treatment Pilot System. (Each of the four columns on left contains a different adsorbent medium. The 3 columns on right contain a single medium (AD33) with different contact times.)

Potential Impact of the Program

The new MCL for arsenic may be one of the most costly health regulations ever promulgated. According to the U.S. EPA (2000), the reduction of the arsenic MCL to 10 ppb will prevent approximately 2.3 to 5.5 deaths from bladder cancer and 4.6 to 27.5 deaths from lung cancer each year in the U.S. The projected annual national compliance cost of implementing the new 10 ppb standard ranges from $165 million, estimated by the U.S. EPA (2000), to $605 million, estimated by AwwaRF (Frey 2000). Based on those calculations by Frost et al. (2002), the estimates of the cost of the implementing the new 10 ppb arsenic standard range from approximately $5 million to $23.9 million per life saved. In addition to these costs, risks associated with implementation of the new standard could increase the cost per life saved considerably. These include 1) risks associated with the use of large quantities of corrosive chemicals in drinking water treatment and traffic accidents related to transport of large amounts of these chemicals (Frost 2001); 2) the economic impacts of the revised arsenic MCL on rural communities, and 3) risks and costs associated with the removal of beneficial constituents along with the arsenic in drinking water. For example, if the 10 ppb EPA MCL for arsenic in drinking water is enforced by the New Mexico Environment Department, monthly water bills for households in small communities in Sandoval, Bernalillo and Santa Fe Counties could reach $100 (Bitner 2001). Depending on the chemical treatment process involved, other negatively charged species such as fluoride could be removed by the water treatment. Although there is considerable controversy surrounding the health benefits of the new arsenic drinking water standard, there is general consensus concerning the health benefits of fluoridation of drinking water. The local health impact of the removal of fluoride will depend on current water treatment practices. In some communities, artificial fluoridation is already occurring and arsenic removal will have little impact. In other communities, naturally occurring fluoride levels are high and additional fluoride treatment has not been necessary to protect oral health. In the future, it may be necessary to include fluoridation as part of the arsenic removal system in such communities. The added costs and the compatibility of fluoridation with arsenic removal processes have not been adequately evaluated.

This program may help to alleviate some of the problems described above 1) by comparing the costs and performance of alternative methods for arsenic treatment in specific community wells in side-by-side pilot tests of several different technologies and 2) by identifying potentially deleterious effects associated with different technologies. As technologies progress from a bench-scale demonstration phase to full-scale commercial production, it is likely that significant cost reductions will be realized. However, at this time, the potential magnitude of cost savings associated with innovative adsorptive media or other treatment processes can not be accurately estimated. Through direct field demonstration and the associated outreach program, this program can provide independent evaluations of the relative merits of the numerous alternative technologic choices that will be presented to communities throughout the U.S. In addition, although the compliance deadline for the new arsenic standard is January 2006, there will be opportunities for water utilities to apply for exemptions, extensions and variances. These will allow communities the time to gather additional information from this and other programs and make a more informed choice of technology. This information might prevent expensive mistakes from being made by small communities, especially those that have few technical or financial resources to carry out adequate assessments of the claims made by vendors about their products.

Finally, an additional objective of the AWTP is to evaluate the efficacy of innovative technologies to treatment of other contaminants. The U.S. EPA is considering new regulations for other naturally occurring contaminants. During the next few years, the new arsenic MCL will result in modification of many rural water systems that otherwise would not require treatment. Identification of multi-use treatment technologies in the near future could lead to considerable long-term cost savings. Simultaneous improvement of water quality in systems that will require treatment for other contaminants such as uranium, radon and radium would be an added benefit of this program.

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Appendix A: Rapid Small-Scale Column Test (RSSCT) Scaling Equations

Crittenden et al. (1986, 1987, 1991) developed scaling equations for both constant and non-constant diffusivities with respect to particle size. The scaling laws ensure that the RSSCT and the full-scale system will have identical breakthrough profiles. The basis for the RSSCT scaling laws is described in this appendix; variables are defined in Table A.

Table A. Definition of Terms for RSSCT Scaling Equations

D_s	Surface diffusion coefficient, L^2/T
$EBCT$	Empty bed contact time, T
k_f	Film transfer coefficient, L/T
LC	Subscript denoting large column
R	Particle radius (geometric mean), L
Re	Reynold's number (dimensionless)
SC	Subscript denoting small column
Sc	Schmidt number (dimensionless)
x	Diffusivity factor (dimensionless)
ε	Void fraction (dimensionless)
μ	Viscosity of the fluid, M/LT
v	Superficial velocity (hydraulic loading), L/T

By equating the modulus of surface diffusivity and assuming equal solute distribution parameters, a relationship between EBCTs for small- and large-scale columns is determined:

$$\frac{EBCT_{SC}}{EBCT_{LC}} = \left[\frac{R_{SC}}{R_{LC}}\right]^2 \frac{D_{s,LC}}{D_{s,SC}}$$

The dependence of the surface diffusion coefficient on particle radius is defined by the diffusivity factor, x, as follows:

$$\frac{D_{s,SC}}{D_{s,LC}} = \left[\frac{R_{SC}}{R_{LC}}\right]^x$$

Combining these equations yields:

$$\frac{EBCT_{SC}}{EBCT_{LC}} = \left[\frac{R_{SC}}{R_{LC}}\right]^{2-x}$$

A special case of non-constant diffusivity is a linear relationship between surface diffusivity and particle size (proportional diffusivity, PD). The diffusivity factor, x, becomes equal to one and the ratio of EBCTs becomes:

$$\frac{EBCT_{SC}}{EBCT_{LC}} = \frac{R_{SC}}{R_{LC}}$$

A minimum value of Re_{SC} is required to establish a minimum velocity that will not over exaggerate the effects of dispersion and external mass transfer. If the small and large columns maintain a constant ratio of their respective Reynolds numbers, the following relation is established:

$$\frac{\mathrm{Re}_{SC,\min}}{\mathrm{Re}_{LC}} = \frac{2v_{SC}R_{SC} / \mu\varepsilon}{2v_{LC}R_{LC} / \mu\varepsilon}$$

Canceling terms and rearranging gives the ratio of the hydraulic loading of the two columns:

$$\frac{v_{SC}}{v_{LC}} = \frac{R_{LC}}{R_{SC}} \frac{\mathrm{Re}_{SC,\min}}{\mathrm{Re}_{LC}}$$

Berrigan (1985) showed that dispersion was not important if the product of the Reynolds and Schmidt numbers was in the mechanical dispersion region, therefore the ratio of hydraulic loadings could be calculated using:

$$\frac{v_{SC}}{v_{LC}} = \frac{R_{LC}}{R_{SC}} \frac{\mathrm{Re}_{SC,\min} Sc_{SC}}{\mathrm{Re}_{LC} Sc_{LC}}$$

A requirement for using this equation is that Pe_{SC} must be greater than or equal to Pe_{LC}, otherwise, a reduction in the hydraulic loading may cause a significant amount of dispersion in the RSSCT (constant diffusivity, CD).

If the surface diffusivity remains constant with respect to the particle radius, then the diffusivity factor, x, is equal to zero and the ratio of EBCTs for small columns and large columns is:

$$\frac{EBCT_{SC}}{EBCT_{LC}} = \left[\frac{R_{SC}}{R_{LC}}\right]^2$$

The Stanton and Peclet numbers remain equal between the small scale and full-scale columns only if the surface diffusivity is independent of particle size. If Stanton numbers are identical between process sizes, then the liquid phase mass transfer coefficients can be related to particle radius by:

$$\frac{k_{f,SC}}{k_{f,LC}} = \frac{R_{LC}}{R_{SC}}$$

If this is the case, the hydraulic loading of the columns is inversely proportional to particle size (Crittenden, et. al., 1987):

$$\frac{v_{SC}}{v_{LC}} = \frac{R_{LC}}{R_{SC}}$$

This relationship will provide equality between Reynold's numbers for both process sizes.

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