United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

Research and Development

EPA-600/S2-84-018 Mar. 1984

Project Summary

A Mobile Drinking Water Treatment Research Facility for Inorganic Contaminants Removal: Design, Construction, and Operation

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A mobile inorganics removal research facility consisting of a pilot plant and analytical laboratory was designed and constructed and has been operated for 3 years. Ion exchange, activated alumina adsorption, reverse osmosis, and electrodialysis have been studied in this transportable facility for the removal of fluoride, nitrate, and chromium. Plans call for the study of arsenic and selenium and any other inorganic contaminants of interest. To date, the facility has performed very well and much valuable pilot-scale data have been obtained.

This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

An estimated several thousand public water supplies in small communities in the United States contain fluoride, nitrate, arsenic, selenium, radium, barium, or chromium in concentrations exceeding the maximum contaminant limits (MCL's) established in the National Interim Primary Drinking Water Regulations. Previous experience and research indicate that these primarily ionic contaminants can be removed by advanced water treatment processes such as packed beds of activated alumina, ion-exchange resins, or by separation using reverse osmosis or electrodialysis. But reliable design criteria and economical operating procedures are not available for the selection, cost-effective application, and safe operation of these processes. Such is especially true for small community water supply treatment, where single contaminant removal is desired in waters containing more than 1000 mg/L of total dissolved solids.

To provide help for small communities, a long-term, EPA-funded project has been undertaken to evaluate the single contaminant removal processes (activated alumina and ion exchange) versus the desalting processes (electrodialysis with reversal and reverse osmosis). To accomplish this project, contaminated water sources in a series of small U.S. communities are being studied with the use of a mobile drinking water treatment research facility.

This report describes the field research capabilities of the 3.2- by 12.5-m (10-by 40-ft) transportable research facility and summarizes its design, construction, and operation. The mobile facility contains a complete analytical laboratory and an 8-L/min (2 gpm) pilot plant with interconnected reverse osmosis, ion exchange, activated alumina, and electrodialysis units. The treatment technologies applicable to a given contaminant removal problem are operated separately over a period of several months. The resulting performance data for all processes are then compared on technical and economic bases, and appropriate general recommendations are made for that type of contaminant removal problem. To date, fluoride, nitrate, and chromium removal have been studied in Taylor, Texas; Glendale, Arizona; and Scottsdale, Arizona, respectively. The 1982 replacement cost of the facility is approximately $200,000.

Inorganic Contaminant Removal Processes

Five of the inorganic contaminants listed in the EPA National Interim Primary Drinking Water Regulations are anions or generally occur as anions in the waters where they are found. These contaminants are fluoride, nitrate, arsenic, selenium, and chromium. Details of their speciation as a function of pH appear in Table 1 along with their MCL's.

Two distinct types of processes may be considered for removing these ions from drinking water: single contaminant removal processes (e.g., alumina adsorption and ion exchange) and desalting processes (e.g., electrodialysis and reverse osmosis). Single contaminant removal generally costs less, but desalting yields a softer, more palatable, and less corrosive water for distribution. Each contaminant removal application will be different because the background raw waters have different total dissolved solids levels and chemical compositions. Both desalting and single contaminant removal processes should therefore be available when doing contaminant removal research.

The literature indicates that fluoride, arsenite, arsenate, selenate, and selenite can be removed from low or high total dissolved solids water supplies by precipitation or coprecipitation with lime, alum, or iron salts. Unfortunately, precipitation processes are not readily adaptable to small water systems or individual wells that must operate on demand. The negative features of coagulation-precipitation processes in these applications include the need for sludge collection, dewatering, and disposal and long start-up and shut-down periods.

Fluoride and arsenic have been removed from water supplies using packed beds of bone char or tricalcium phosphate. But these media tend to degrade by attrition and continuously lose capacity after successive regenerations. Packed beds of activated alumina and anion exchange resins have been chosen for this single contaminant removal research. Such columns can be operated on demand and are generally free from the disadvantages of precipitation processes and packed-bed processes using bone char and tricalcium phosphate.

For desalting small flows of brackish water, electrodialysis and reverse osmosis are the methods of choice. Electrodialysis removes ions from water; reverse osmosis removes water from ions. In both processes, low-molecular-weight (<200), uncharged species tend to pass through into the product water. But properly operated reverse osmosis units will remove bacteria, viruses, and silica, whereas electrodialysis units will not. Finally, these desalting processes may be expected to do a fair-to-good job of removing the inorganic contaminants of interest even in high (>1000 ppm) total dissolved solids waters. The single contaminant removal and desalting processes to remove fluoride, nitrate, and the various forms of arsenic and selenium can be compared in Table 2. Entries in the table are primarily based on theory and bench-scale research findings, except for fluoride removal, which has been practiced on a large scale.

Table 1. *Potential Anionic Contaminants for Water Supplies*

Contaminant	MCL, mg/L	Common Form in Ground Water (pH=6-9)
Fluoride	1.6*	F^-
Nitrate (as N)	10.	NO_3^-
Arsenic	0.05	$H_2AsO_4^-$, $HAsO_4^=$, $HAsO_2$, AsO_2^-
Selenium	0.01	$SeO_4^=$, $SeO_3^=$, $HSeO_3^-$
Chromium	0.05	$HCrO_4^-$, $CrO_4^=$

*Annual average of maximum daily air temperature = 70.7 - 79.2°F.

Mobile Research Concept

The reusable pilot-plant concept was thought to be particularly applicable to the diverse inorganic contamination problems in small communities. In early 1979, work was started in earnest on an EPA-funded research project at the University of Houston (UH) to design, construct, and operate a transportable, reusable, pilot-plant facility for inorganic contaminant removal. This is the design and construction report for the transportable pilot plant, which was completed in April 1980. As of December 1982, it has been operated in Taylor, Texas, for fluoride removal; in Glendale, Arizona, for nitrate removal; and in Scottsdale, Arizona, for chromate removal. Experience from the first three moves has shown that the facility is readily transportable and reusable. The pilot-scale treatment systems have operated very well, and much valuable pilot-scale data have been obtained.

Table 2. *Potential* for Contaminant Removal by Various Treatment Processes*

	Packed Beds		Reverse Osmosis	Electrodialysis
Contaminant	Activated Alumina pH 5.5 - 7.5	Strong Base Resins pH 5-9	Cellulose Acetate or Aromatic Polyamides pH 6 - 8	pH 6 - 8
Fluoride	G⁺	P	G	G
Nitrate	P	F	F/G	F/G
Arsenic (III)	F/P	P[1]	P/F	P/F
Arsenic (V)	G	P/G[2]	G	G
Selenium (IV)	G	F[3]	G	G
Selenium (VI)	F	G[4]	G	G
Chromium (VI)	F	G	G	G

*Potentials are based on published experimental results except where noted:
[1] H_3AsO_3, the uncharged species, predominates at pH's below 9.2
[2] Poor at pH's below 7 ($H_2AsO_4^-$), good at pH's above 7 ($HAsO_4^=$)
[3] Estimated, based on the elution of selenite in ion chromatography
[4] Estimated, based on the elution of selenate in ion chromatography
⁺G = Good F = Fair P = Poor: These are relative rankings for the process in question. For electrodialysis, and reverse osmosis at 50% to 80% recovery:
Good means greater than 80% removal in typical ground water,
Fair means 40% to 80% removal,
Poor means less than 40% removal.
For packed bed processes:
Good means that the ion is highly preferred relative to Cl^-,
Fair means that the ion is a preferred ion relative to Cl^-,
Poor means that the ion is not a preferred ion relative to Cl^-.

The mobile water treatment pilot-plant system (Figure 1) consists of a 3.2 x 12.5-m (10- x 40-ft) research trailer, a pick-up truck containing a 1160-L (300-gal) wastewater tank, and a 9.7-m (31-ft) travel trailer. The research trailer (Figure 2) is transported between sites by a professional tractor-trailer driver, and the travel trailer is pulled by the pick-up truck driven by the field researcher. While on location in the field, connections are made to the research trailer to supply raw water (an average of 8 L/min), electrical power (100A, 220V), and telephone service. Unused treated waters and nontoxic wastewaters are disposed of through discharge lines to a nearby sewer or by surface spreading (grass watering). Toxic wastewaters (e.g., concentrated As or Se solutions) will be pumped into an 1160-L (300-gal) tank in the pick-up truck and transported to an ultimate disposal site.

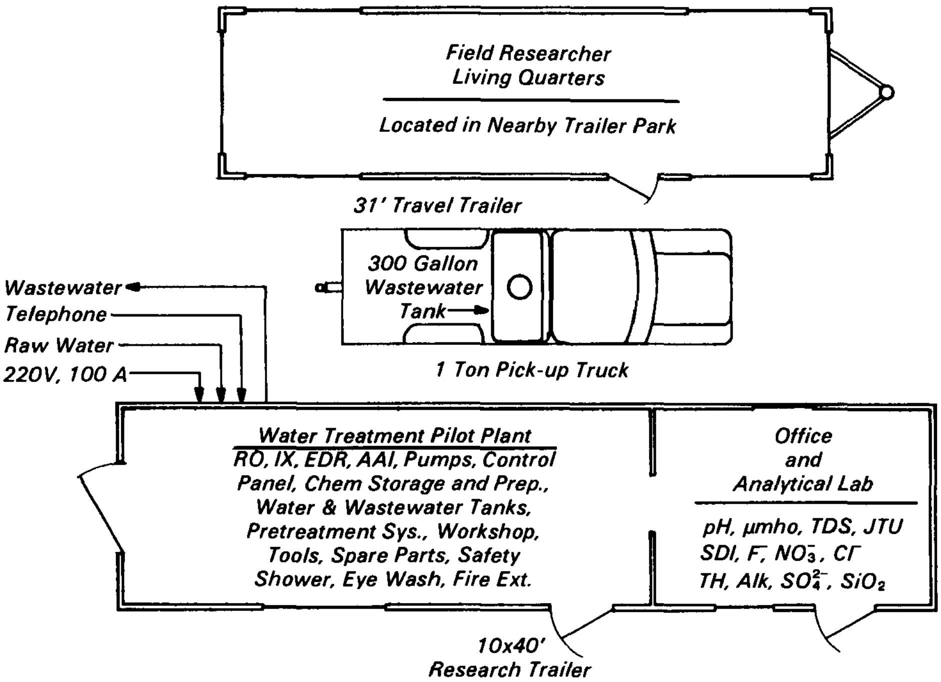

Figure 1. *Mobile research concept including transportable pilot plant/laboratory, travel trailer, pickup truck.*

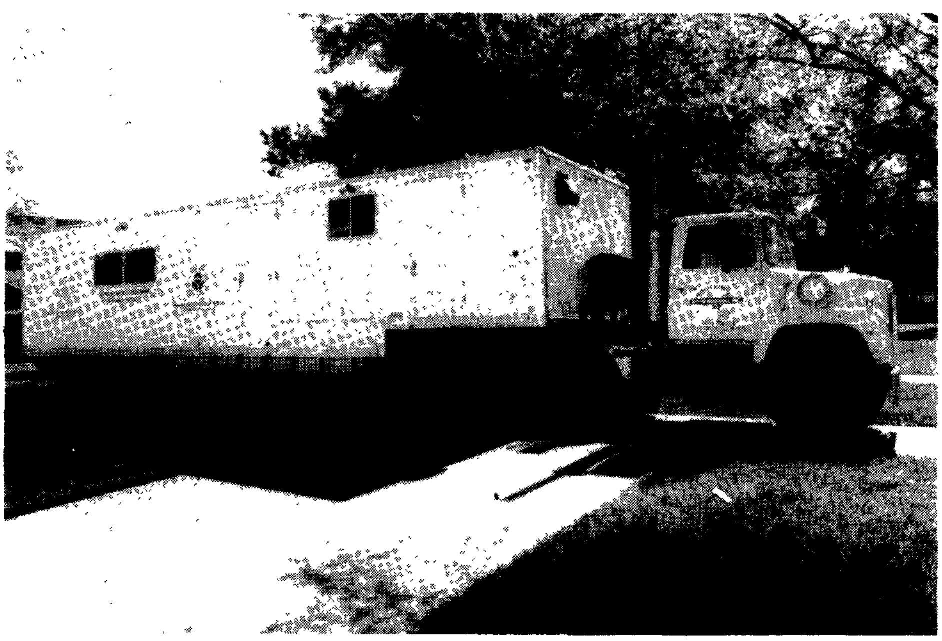

Figure 2. *UH/EPA mobile drinking water treatment research facility shown hooked up to contract hauler's tractor leaving the University of Houston on its way to Taylor, Texas.*

During the 3- to 12-month period at a given field location, the field researcher lives in the travel trailer. The latter is generally located in a nearby trailer park where complete utility hookups are available.

Water treatment process research and water analyses are both done in the large research trailer, which is divided into two sections (Figure 1). The rear two-thirds of the space is devoted to the pilot plant, and the front third contains the analytical laboratory and office. Ideally, the field researcher is an environmental or chemical engineer with analytical chemistry skills. He or she does both the pilot-plant experiments and the water analyses or supervises the water analyses. Other personnel involved in the research include the principal investigator (PI), environmental engineering graduate students, a part-time analytical chemist, and outside contractors. The PI supervises the design and execution of all experiments by phone, letter, and site visits. Graduate students are occasionally sent to the field locations to assist the field researcher for periods of 2 to 6 weeks. Part-time chemists who are local residents are used to assist in the analytical work whenever possible. Finally, outside contractors are hired to move the trailer, install the electrical power, and maintain the instruments and control systems.

Selecting Field Locations for Study

Small community water supplies to be evaluated for contaminant removal studies are selected by the PI on the basis of:

(1) Severity of the inorganic contaminant levels and demonstrated health effects.

(2) Usefulness of the results to the community and the degree of cooperation expected (determined by earlier communications and a site visit by the PI).

(3) Levels of total dissolved solids and competing ions, especially sulfate. High total dissolved solids (>1000 ppm) supplies are of particular interest for comparing the desalting technologies with the single contaminant removal processes. Sulfate is of special interest because it competes favorably with the contaminants for adsorption sites on alumina and anion exchange resins.

(4) Presence of foulants such as iron, manganese, silica, and organics. Attempts will be made to choose water supplies so that each of these foulants will eventually be studied.

(5) Agreement by EPA (Drinking Water Research Division) and state and local governments that the supply to be studied will produce useful and timely results.

General Specifications and Layout

The research trailer is 3.2 m (10 ft) wide rather than the usual 2.5 m (8 ft) to provide a safe and comfortable working environment for the field researchers. Mobile offices and homes were available in the 3.7-m (12-ft) width as the basic unit, but they were rejected as being too wide and flimsy for rugged use and repeated moving. The basic trailer shell was constructed of aluminum according to UH specifications by General Truck Body, Inc., of Houston, Texas, on a twin I-beam, 8-wheel chassis. Though the 3.2-m-wide (10-ft) trailer is considered a wide load, permits to move it are readily obtained by contract haulers. Since 98 percent of the time the unit is in fixed-locations and only 2 percent in transport, the extra space, comfort, and safety realized while it is stationary more than compensate for the slight disadvantage of transporting a wide load.

The pilot plant and the laboratory sections have separate entrance doors, and each entrance is provided with a removable stairway and an attached safety railing. In addition, the pilot plant section has an extra wide (46-in., 1.17-m) equipment door that doubles as an emergency exit. A sliding door inside the trailer allows the pilot plant to be isolated from the analytical laboratory. Six flood lights are mounted high up on the outside of the trailer. These automatically turn on at night to illuminate the entrances and the area around the trailer to help minimize vandalism. One double window in the pilot plant and two single windows in the laboratory provide ventilation, natural lighting, and a view of the surrounding area.

A special effort was made to fasten rigidly all of the pilot plant and laboratory equipment either to the floor or walls for protection during transit. Unistrut channels were used throughout the trailer on the walls and ceiling for mounting the flow system piping and components and the PVC electrical conduit and control boxes. Also, weatherproof electrical outlets, wall-switches, and control enclosures were used throughout the pilot plant and lab for protection against possible process spills.

Corrosion-resistant plastics (PVC, Plexiglas,* Teflon, polyethylene, and nylon) were used wherever possible for the pumps, valves, columns, and piping. The widespread use of plastics would not have been possible if organic rather than inorganic contaminants were being studied. Stainless steel, nylon, and fiber-glass-reinforced plastics were used in the reverse osmosis system, where pressures in excess of 2760 kPa (400 psig) are expected. Finally, the pilot plant components were duplicated in the system design wherever possible to provide readily available replacements in the event of failure.

The treatment processes are laid out in a left-to-right flow scheme on one wall of the pilot plant (Figures 3 and 4). The feedwater, acid and base tanks, and pumps are located on the left side of the four processes, and the 200-L (55-gal) polyethylene, treated-water and waste-water collection tanks and pumps are on the right. Larger 1160-L (300-gal) fiber glass water and wastewater storage tanks are mounted underneath on either side of the trailer. Each of the treatment processes is controlled from the graphic control panel mounted on the process wall above the reverse osmosis unit. Facing the control panel, the operator stands within easy reach of both the process equipment and the graphic controls. This arrangement is considered an important safety and convenience feature for the complex one-man research operation.

*Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Work and storage areas occupy the wall across from the processes. The work benches are used for equipment repair, chemical preparation, and storage. Two 2.13-m-high x 1.19-m-wide (7-ft x 47-in.) storage cabinets are provided for spare parts, resins, alumina, and chemicals, and the hand tools are kept in a rolling tool chest. A safety shower and eyewash fountain are located in the chemical preparation area near the utility sink. The analytical laboratory layout features standard laboratory furniture with cast epoxy bench tops and color-coded drawer fronts (Figure 4). The laboratory also serves as the project's field office. As such, it contains a desk, file cabinet, book shelf, and telephone.

The laboratory is equipped to analyze raw and treated waters for pH, dissolved solids, fluoride, chloride, nitrate, chromate, hardness, alkalinity, sulfate, and silica by the usual wet chemical methods. In addition, instrumentation has also been provided to measure conductivity, turbidity, silt density index (SDI), and Cl^-, F^-, and NO_3^- ions using electrodes. Recently, an ion chromatograph was added for routine analysis of the common

Figure 3. *Pilot plant in mobile research facility. This view of the trailer is from rear to front, with treatment processes on the left, work and storage areas on the right, and the door opened to the laboratory in the center of the picture.*

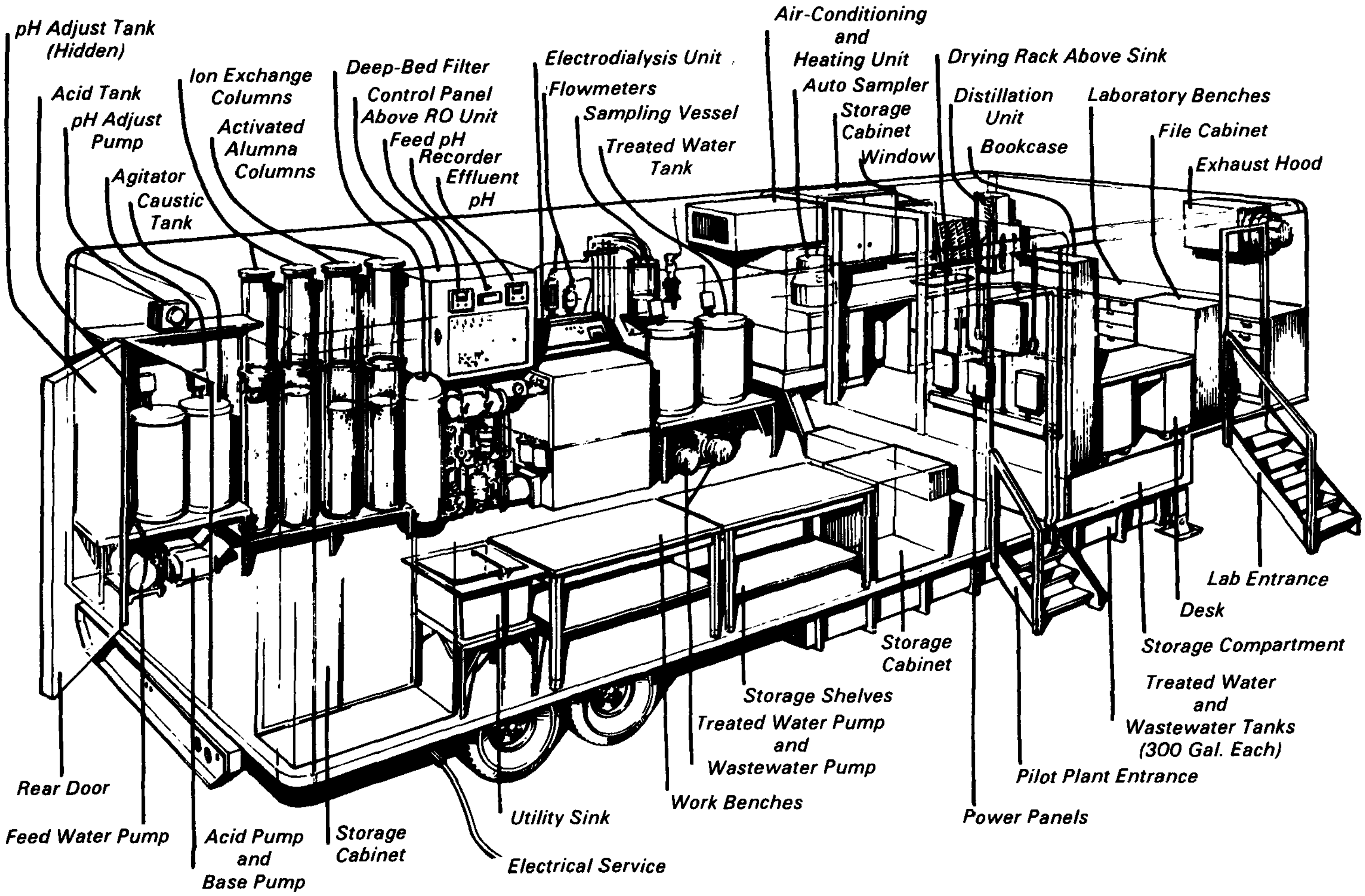

Figure 4. Interior layout of the UH/EPA drinking water treatment research facility showing both the pilot plant and laboratory equipment.

anions F^-, Cl^-, Br^-, NO_3^- and $SO_4^=$. A rugged atomic absorption spectrophotometer with a graphite furnace atomizer will be provided whenever the research trailer is being used to study arsenic or selenium removal. Most of the water samples to be analyzed, especially product water and regenerants, are collected automatically by the automatic sampler at times preselected by the field researcher. Other grab samples of the raw water and brine streams are collected when necessary.

Pilot Plant Treatment Units

The primary components of the pilot plant are the four treatment units. Though they are interconnected, they were designed to be operated one at a time rather than simultaneously. Each unit may be operated over a wide range of feed and product water flow rates.

The 8-L/min (2-gpm) activated alumina system is made up of two 20.3-cm-diameter (8-in.) Plexiglas columns containing 0.91 m (3 ft) of 28 x 48 mesh Alcoa F-1 activated alumina. The columns may be operated in series or parallel with upflow or downflow exhaustion and regeneration. The intended uses of the alumina system are for fluoride, arsenic, and selenium removal. Regeneration is accomplished using dilute (0.25 N) sodium hydroxide followed by acidification with dilute (0.50 N) sulfuric acid. Spent regenerants are either reused or neutralized and disposed of locally.

The 8-L/min (2-gpm) ion-exchange system is made up of two 25.4-cm-(10-in.-) diameter Plexiglas columns typically containing 0.91-m (3 ft) of anion or cation exchange resin. Single-bed or two-bed ion-exchange processes may be simulated with either upflow or downflow exhaustion and regeneration. Single-bed anion exchange with sodium chloride regeneration is the intended method for removal of nitrate, arsenic, selenium, and chromate. As with the alumina system, backwashing may be accomplished with raw water or with treated water from the storage tanks. In fact, with the exception of the column diameters, the alumina and ion-exchange systems are identical and may be used interchangeably. Tanks and pumps have been provided so that both the ion exchange and alumina systems may be regenerated or cleaned with acids, bases, or salts in any conceivable sequence.

The reverse osmosis desalting system is made up of two, different, standard, hollow-fiber modules that may only be operated one at a time. The DuPont aramid module has a nominal product water flow of 5.52 L/min (1.45 gpm) and operates at a typical feed pressure of 2415 kPa (350 psig) with a typical product water recovery of 50 percent. The Dow cellulose triacetate module is considerably larger, with a nominal product flow of 10.5 L/min (2.78 gpm), a feed pressure of 2415 kPa (350 psig), and 50 percent recovery. Both units have typical overall dissolved solids rejections in the range of

95 to 98 percent and will be used to remove any contaminant ion of interest. As with the reverse osmosis and ion exchange units, the reverse osmosis product water may be stored temporarily or disposed of locally with the rejected brine. Proper pretreatment is known to be the key to successful reverse osmosis system operation, so the pilot plant has been designed with means for dechlorination, polymer addition, deep-bed filtration, and cartridge filtration.

The reversible electrodialysis desalting system was purchased as a complete unit from the manufacturer, Ionics, Inc. The nominal product-water flow rate is 1.31 L/min (0.35 gpm), and the recovery varies from 50 to 80 percent, depending on the amount of brine recycled. As with the reverse osmosis unit, the reversible electrodialysis unit will be used to study the removal of all contaminant ions of interest. Compared with reverse osmosis, very little pretreatment is required for reversible electrodialysis, and the system operates with only cartridge prefiltration and dechlorination using an activated carbon filter. A membrane cleaning system using acids and/or chelating agents has been provided for cleaning the reverse osmosis and reversible electrodialysis membrances as required.

The full report was submitted in fulfillment of Cooperative Agreement No. CR806073 by the University of Houston under the sponsorship of the U.S. Environmental Protection Agency.

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The complete report, entitled "A Mobile Drinking Water Treatment Research Facility for Inorganic Contaminants Removal: Design, Construction, and Operation," (Order No. PB 84-145 507; Cost: $10.00, subject to change) will be available only from:
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