Field Demonstration of Permeable Reactive Barriers to Control Radionuclide and Trace-Element Contamination in Ground Water from Abandoned Mine Lands

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ABSTRACT

Pump-and-treat methods are costly and often ineffective in meeting long-term protection standards for contaminated ground water. Permeable reactive barriers (PRBs) may offer a cost-effective alternative to other ground-water remediation methods. A PRB functions as a passive in-situ treatment zone that degrades or immobilizes contaminants. A demonstration project is currently (1999) underway at an abandoned uranium upgrader operation site in southeastern Utah to evaluate the removal of uranium from ground water by using six different PRBs. Two methods of PRB deployment, the funnel and gate design and non-pumping well design, were installed to passively treat uranium-contaminated ground water. The six different PRBs have removed uranium from the ground water with various levels of efficiency. With respect to the PRBs installed using the funnel and gate design, the barrier containing zero-valent iron has consistently removed more than 99.9 percent of the input uranium concentration during the first year of operation. The percentage of uranium removed in the bone char phosphate and amorphous ferric oxyhyroxide PRBs was slightly less, averaging 94.0 and 88.1 percent, respectively. The three barrier deployment tubes in the non-pumping wells containing mixtures of bone-char phosphate and iron-oxide pellets removed less uranium than the PRBs deployed using the funnel and gate design. Numerous geochemical and hydrological factors that affect uranium removal efficiencies and processes in each of the PRBs are currently (1999) being evaluated.

INTRODUCTION

Potable ground-water supplies worldwide are contaminated or threatened by advancing plumes containing radionuclides and metals. Pump-and-treat methods are costly and often ineffective in meeting long-term protection standards (Travis and Doty, 1990; Gillham and Burris, 1992; National Research Council, 1994). Alternative, cost effective approaches to pump-and-treat methods could have widespread applicability to abandoned and active mine sites throughout the United States and other parts of the world.

Permeable reactive barriers (PRBs) are potentially cost-effective alternative technology to pump-and-treat methods. A PRB is a permanent, semi-permanent, or replaceable unit that is installed across the flow path of a contaminant plume (RTDF Permeable Reactive Barriers Action Team, 1998). A PRB contains a zone of reactive material that acts as a passive in-situ treatment zone. This in-situ treatment zone degrades or immobilizes contaminants, such as radionuclides and other trace elements, as ground water flows through it (fig. 1). Operational and maintenance costs are lower because water flow across the PRBs is driven by the natural gradient and the treatment system does not require operational maintenance. Reactions within the

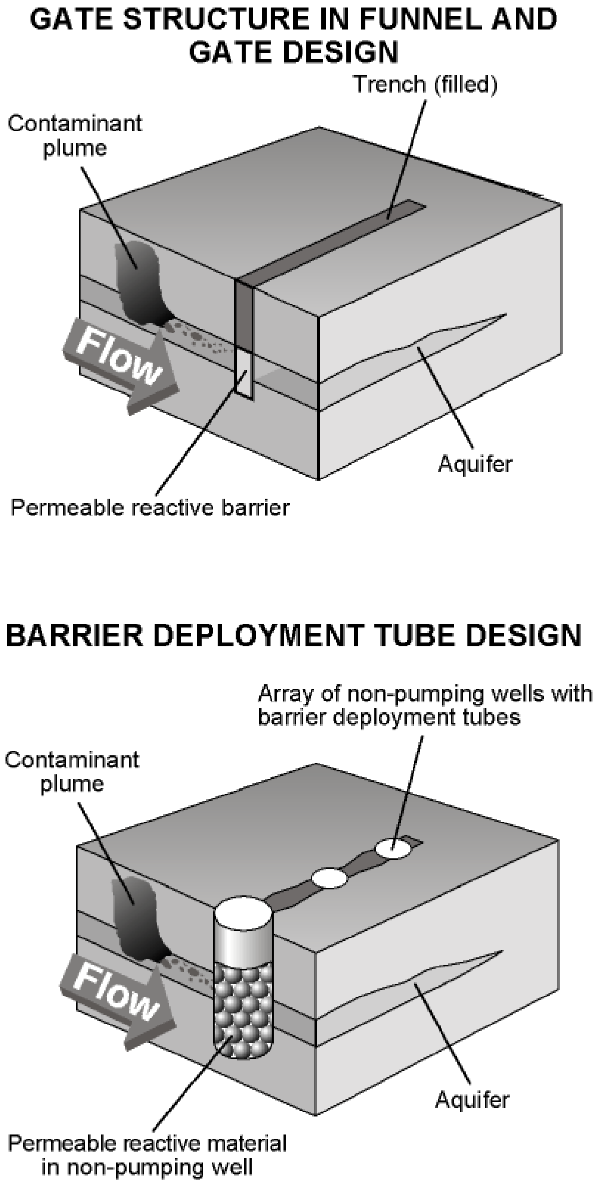


Figure 1. Schematic diagrams of permeable reactive barriers currently being demonstrated at Fry Canyon, Utah.

PRB material either degrade contaminants to non-toxic forms or transfer the contaminants to an immobile phase. Potential limitations to PRBs include re-release of contaminants after aging of reactive material, removal and disposal of the reactive material after breakthrough, and deleterious effects of barrier material on downgradient water quality.

The project is currently (1999) testing six different PRBs and two different deployment techniques at the Fry Canyon demonstration site

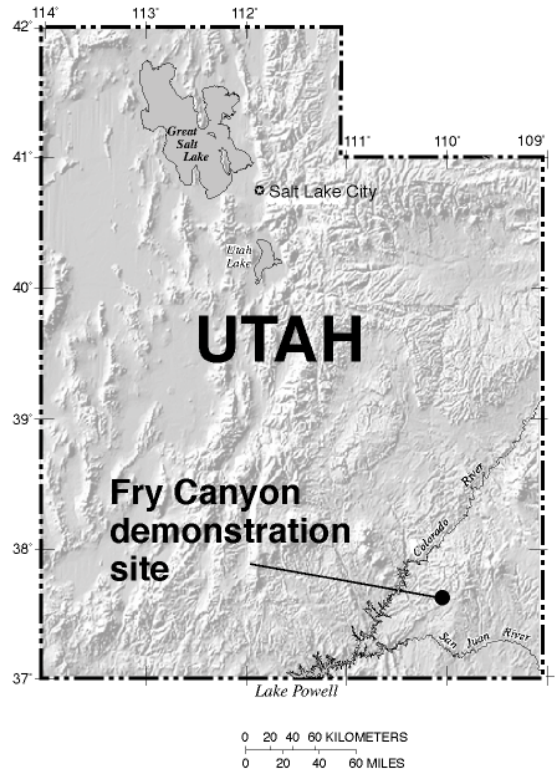


Figure 2. Location of the Fry Canyon demonstration site in southeastern Utah.

in southeastern Utah (fig. 2). This site is an abandoned uranium upgrader operation on Federal land managed by the Bureau of Land Management (BLM). The shallow ground water in the colluvial aquifer is contaminated with elevated concentrations of uranium that can exceed 20,000 micrograms per liter (µg/L). Objectives of this paper are to describe the techniques used for installation and monitoring of PRBs and present the initial results of PRB performance during the first year of field demonstration. The U.S. Environmental Protection Agency (USEPA)/Superfund and Office of Radiation and Indoor Air and the U.S. Geological Survey Technology Enterprise Office provided funding for this ongoing project.

INSTALLATION AND OPERATION

Funnel and gate PRBs

A funnel and gate design was chosen to demonstrate three of the six PRBs installed at the site (fig. 1). Funding for this installation was provided by the U.S. Environmental Protection Agency (USEPA)/Superfund and Office of Radiation and Indoor Air. This design consisted of three "permeable windows" or gates where each of the PRBs were placed, separated by impermeable walls between the gate structures and impermeable wing walls on each end to channel the ground-water flow into the PRBs. Dimensions of each gate structure are 7 feet long by 3 feet wide by about 4 feet deep. The three PRBs and no-flow walls were keyed into the bedrock (Cedar Mesa Sandstone) underlying the colluvial aquifer. A 1.5-foot-wide layer of pea gravel was placed on the upgradient side of the PRBs to facilitate uniform flow of contaminated ground water into each gate structure. The three barriers consist of (1) bone char phosphate (PO_4); (2) zero valent iron (ZVI) pellets; and (3) amorphous ferric oxyhyroxide (AFO).

The mechanism of uranium removal in each of the PRBs is a function of the type of barrier material. The PO_4 barrier material consists of pelletized bone charcoal used as phosphate source to facilitate formation of insoluble uranyl phosphate compounds. The ZVI barrier material consists of pelletized iron designed to remove uranium by reduction of uranium (VI) to the less soluble uranium (IV). The AFO barrier material consists of pea gravel coated with amorphous ferric oxyhydroxide that removes uranium by adsorption to the ferric oxide surface. Materials were pelletized or used as a coating on gravel to increase the permeability of the gate structure relative to the permeability of the native aquifer material.

Heavy equipment consisting of a track-mounted backhoe and a bulldozer was used to install the PRBs (fig. 3). This design-and-installation technique was used for the following reasons: (1) amenable for multiple PRBs placed side by side; (2) low construction cost; (3) conducive to a shallow ground-water system; and (4) transferability to other remote, abandoned

Figure 3. Placement of reactive material into the gate structure of the bone-char phosphate barrier at Fry Canyon, Utah, during September 1997.

mine sites with shallow contaminated ground water.

Each PRB is instrumented so its performance can be assessed and compared during the demonstration period (fig. 4). Four transducers and a water-quality minimonitor (measuring temperature, pH, specific conductance, oxidation reduction potential, and dissolved oxygen) are deployed in each barrier. Water-level and water-quality data from the instruments are recorded hourly. Flow direction and velocity are measured in each PRB using a flow sensor during site visits at monthly to quarterly intervals. Each PRB has a total of 20 monitoring points for the collection of water-quality samples. Seven monitoring points are located downgradient of the barriers in the colluvial aquifer.

Barrier deployment tubes in non-pumping wells

An array of 6-inch-diameter wells, installed using a cable tool drilling rig, was used to deploy three additional PRBs at the Fry Canyon site (fig. 1). Funding for this installation was provided by the U.S. Geological Survey Technology Enterprise Office. Barrier deployment tubes containing different proportions of bone char phosphate and foamed iron oxide pellets were placed in the large-diameter wells. Use of arrays of unpumped wells has been proposed by Wilson and Mackay (1997) as a method to remediate

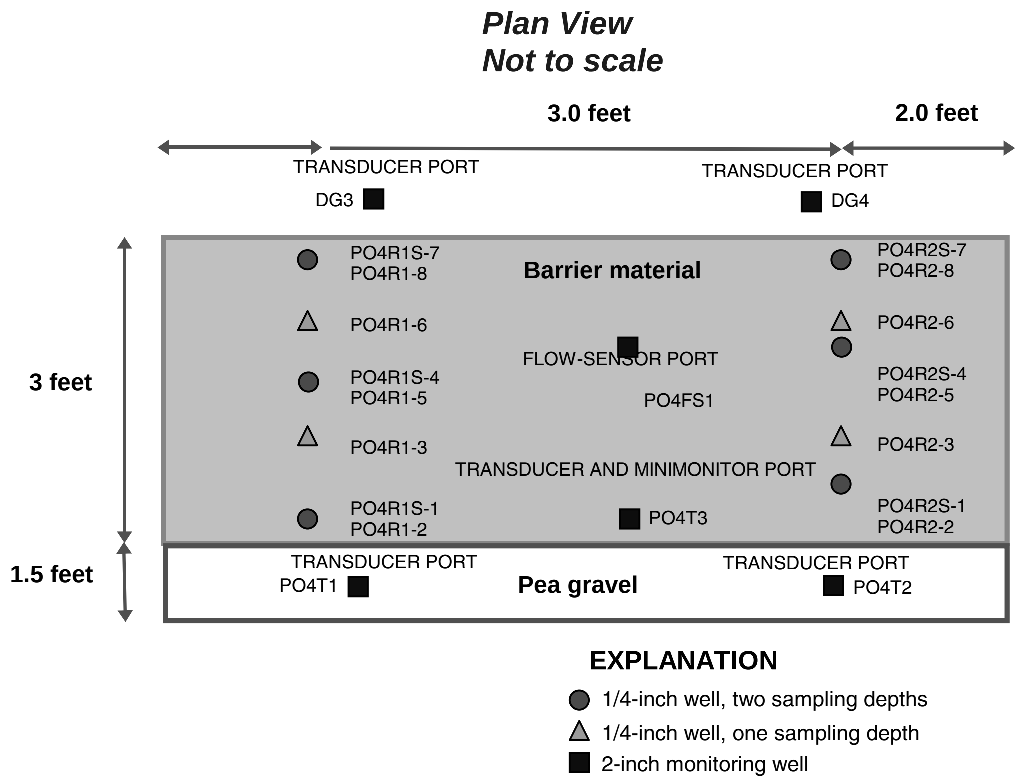


Figure 4. Schematic diagram showing monitoring well placement in the bone char phosphate permeable reactive barrier. The monitoring design in the zero valent iron and amorphous ferric oxide barriers is the same.

contaminant plumes when the installation of treatment walls is not possible because of technical or financial constraints. This type of deployment technology is useful for treatment of deeper contaminant plumes. Use of barrier deployment tubes allows for cost-effective retrieval and replacement of reactive material, which would not be possible with other deployment technologies.

Under natural flow conditions at Fry Canyon, ground water converges to the non-pumping well array and the associated barrier deployment tubes in response to the difference in hydraulic conductivity between the well and aquifer (fig. 5). Numerical simulations of ground-water movement through the non-pumping well array indicate that each well intercepts ground water in a portion of the upgradient aquifer approximately twice the inside diameter of the well (fig. 5).

Three of the barrier deployment tubes were installed on site in October 1998 (fig. 6). Different proportions of bone char phosphate and iron oxide pellets were used to facilitate increased uranium removal from ground water. The iron oxide pellets strongly adsorb the phosphate released from the phosphate pellets. The adsorbed phosphate can then react with the uranium in the ground water to facilitate formation of insoluble uranyl phosphate compounds. The following proportions of bone char phosphate:iron oxide pellets (volume ratio) were used: (1) 25:75 (intermixed), well BZ2; (2) 50:50 (intermixed), well BZ1; and (3) 50:50 (layered verttically), well BZ3. Each barrier package has five monitoring points for the collection of water samples (fig. 6).

RESULTS

Funnel and gate PRBs

One year of uranium-concentration data has been collected from the three PRBs installed using funnel and gate designs (fig. 7). The input uranium concentrations are significantly different for each PRB, ranging from less than 1,000 µg/L in the PO_4 PRB to more than 20,000 µg/L in the amorphous ferric oxyhydroxide (AFO) PRB. The input uranium concentrations to each of the PRBs also vary seasonally by approximately 4,000 to 7,000 µg/L.

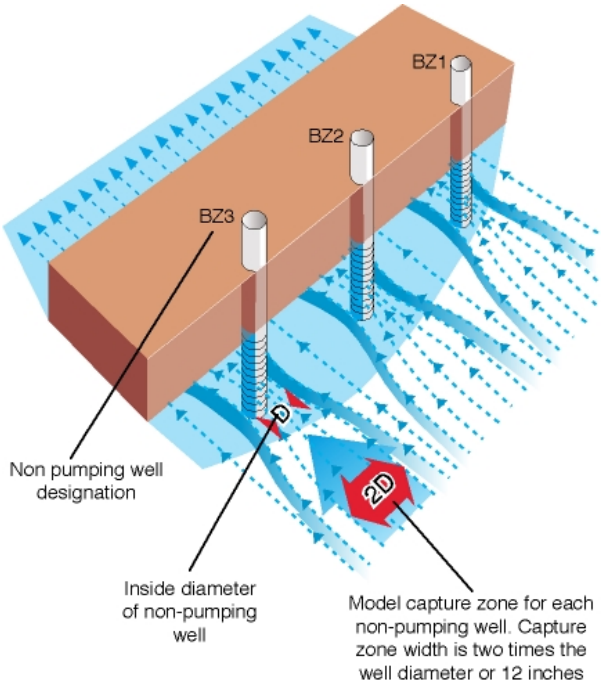


Figure 5. Schematic diagram showing the array of non-pumping wells and modeled ground-water flow paths and capture zones, Fry Canyon, Utah.

During the first year of operation, the PRBs removed most of the incoming uranium (fig. 7); however, the percentage of uranium removal varies with time and barrier material (table 1). Percent uranium removal was calculated using the following formula:

$$U_{removed} = 100 - (U_{barr}/U_{input}) \quad (1)$$

Where

$U_{removed}$ is the percent of uranium removed

U_{barr} is the concentration of uranium in ground water 1.5 feet from the pea gravel/PRB interface

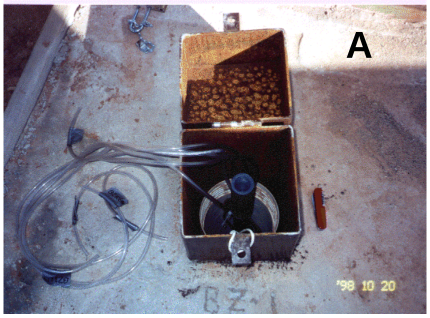
U_{input} is the concentration of uranium in ground water prior to entering the PRB

The zero valent iron (ZVI) PRB has consistently removed more than 99.9 percent of the input uranium concentration in flow-path 1 (table 1). The percentage of uranium removed in the PO_4 and AFO PRBs is slightly less than the ZVI PRB. Except for two monitoring periods, more than 90 percent of the input uranium concentration was removed in the PO_4 barrier. The AFO PRB removed more than 90 percent of the input uranium concentration through November 1997. From January 1998 through September 1998 the uranium removal percentage was reduced to less than 90 percent.

Table 1. Percentage of input uranium concentration removed after traveling 1.5 feet into each of the permeable reactive barriers that were constructed using the funnel and gate design, Fry Canyon, Utah.

Date	PO4 barrier	ZVI barrier	AFO barrier
SEP 1997	99.7	> 99.9	95.3
OCT 1997	94.8	> 99.9	94.9
NOV 1997	89.4	> 99.9	93.6
JAN 1998	79.2	> 99.9	85.9
APR 1998	96.7	> 99.9	77.8
JUN 1998	98.3	> 99.9	81.9
SEP 1998	> 99.9	> 99.9	87.4

Numerous geochemical and hydrological factors that affect uranium removal efficiencies and processes in each of the PRBs are currently (1999) being evaluated. These factors include changes in the amount and velocity of water flowing through the PRBs, type and quantities of minerals forming within the PRBs, leakage between no-flow boundaries between the PRBs, small-scale ground-water flow paths through the PRBs, and effects of PRBs on downgradient water quality. Downgradient effects from the ZVI PRB may include increased iron concentrations in ground water.



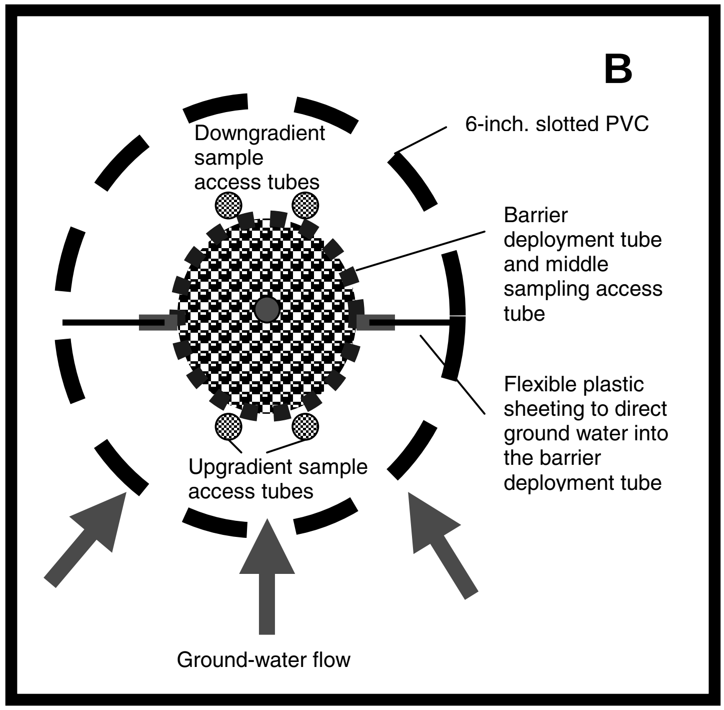


Figure 6. (A) Photograph of non-pumping well BZ1 after deployment of barrier deployment tube and (B) schematic diagram of barrier deployment tube and location of sample access ports.

Barrier packages in non-pumping wells

Three months of uranium-concentration data have been collected from the three barrier deployment tubes (fig. 8) that were installed in the non-pumping well array. During this initial operation, the barrier deployment tubes were removing less uranium than the PRBs deployed using the funnel and gate design. For example, during the first year of operation the PO_4 PRB removed an average of 94 percent of the input uranium after traveling 1.5 feet into the barrier material. In October 1998, the average percent removal of uranium from the three barrier deployment tubes was 67 percent. This removal percentage was calculated using equation 1. Possible explanations for the lower removal efficiencies in the barrier deployment tubes could include mixing of bone char phosphate material with the foamed iron source, reduced flow-path lengths, shorter reaction times, uncertainty in small-scale ground-water-flow directions, and artificial gradients introduced during sampling.

SUMMARY

During the initial period of operation, the six different PRBs removed uranium in the ground water with various levels of efficiency. With respect to the PRBs installed using the funnel and gate design, the ZVI barrier consistently removed greater than 99.9 percent of the input uranium concentration during the first year of operation. The percentage of uranium removed in the PO_4 and AFO barriers was slightly less during the same operation period. The three barrier deployment tubes removed less uranium than the PRBs deployed using the funnel and gate design. During October 1998 the average removal of uranium from the three barrier deployment tubes was 67 percent. Numerous geochemical and hydrological factors that affect uranium removal efficiencies and processes in each of the PRBs are currently (1999) being evaluated.

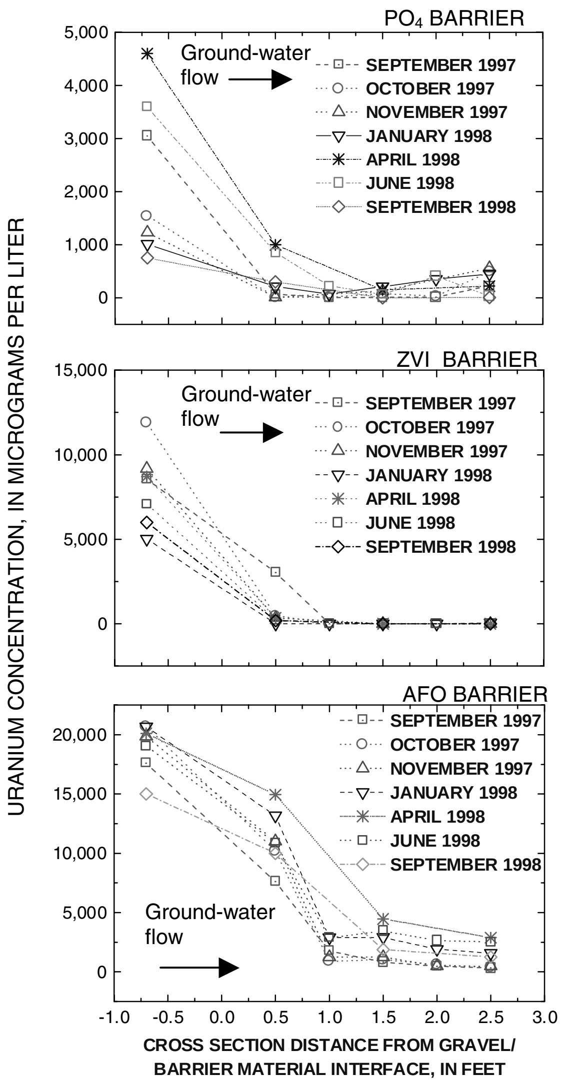


Figure 7. Changes in dissolved uranium concentrations in the three permeable reactive barriers installed using the funnel and gate design, Fry Canyon, Utah.

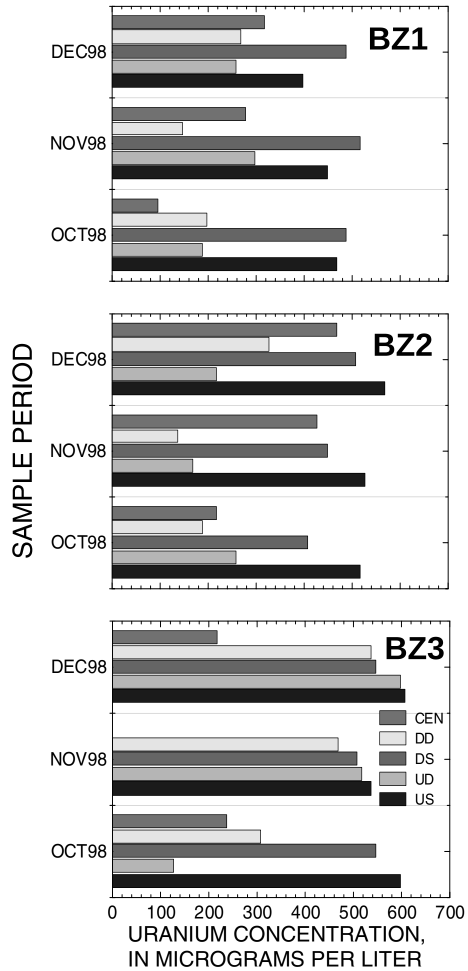


Figure 8. October, November, and December 1998 uranium concentrations in water samples taken along the perimeter and center parts of the barrier deployment tubes, Fry Canyon, Utah. Preinstallation uranium concentration in October 1998 was 635 micrograms per liter. The CEN, DD, DS, UD, and US designations refer to individual sample tubes on each of the barrier deployment tubes.

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