



Sorption and Leaching of Trace-Level Metals by Polymeric Well Casings

Thomas A. Ranney and Louise V. Parker

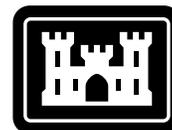
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Abstract

The most commonly used well casing materials (polyvinyl chloride [PVC], polytetrafluoroethylene [PTFE] and stainless steel) cannot be used for all monitoring applications. Therefore, a series of experiments was conducted to compare three alternative polymeric well casing materials (fluorinated ethylene propylene [FEP], fiberglass-reinforced epoxy [FRE] and fiberglass-reinforced plastic [FRP]) with PVC and PTFE. These studies were conducted to determine the overall suitability of these materials for use in groundwater monitoring wells. Previous studies compared these materials for sorption of dilute organic solutes, leaching of organic constituents, and resistance to degradation by chemicals, especially organic solvents. This particular study focuses on sorption and leaching of metals. This study shows that the fiberglass materials were more apt to leach metal contaminants than PVC, FEP, and PTFE. Leached concentrations, with one exception (Pb leaching from FRP), were below maximum allowable limits set by the US EPA for drinking water. With respect to sorption, none of the polymers sorbed the anions tested, but all of them sorbed the cations tested. FEP and PTFE were much less sorptive than the other materials. These results and those from our previous studies can be used, along with other considerations, to select a casing material that is best suited for the intended monitoring application and conditions in the well.

For conversion of SI units to non-SI units of measurement consult ASTM Standard E380-93, *Standard Practice for Use of the International System of Units*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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of Engineers**

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PREFACE

This report was prepared by Thomas A. Ranney, Staff Scientist, Science and Technology Corporation, Hanover, New Hampshire, and Louise V. Parker, Research Physical Scientist, Applied Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Funding for this work was provided by the U.S. Army Environmental Center (USAEC), Aberdeen Proving Ground, Maryland, Martin H. Stutz, Project Monitor.

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THOMAS A. RANNEY AND LOUISE V. PARKER

INTRODUCTION

Ideally, any material that is used as either a well casing or screen in a groundwater monitoring well should be strong enough to remain intact once installed in the well, should resist degradation by the environment, and should not affect analyte concentrations in samples by leaching or sorbing organic or metal contaminants. Recent draft RCRA guidance by the U.S. Environmental Protection Agency (US EPA 1992) acknowledges that none of the most commonly used casing materials in groundwater monitoring wells (polytetrafluoroethylene [PTFE], polyvinyl chloride [PVC], or stainless steel [SS]) can be used for all monitoring applications. Therefore, we undertook a series of studies to assess the suitability of several other candidate materials for use in well casings. The four materials we initially considered were acrylonitrile butadiene styrene (ABS), fluorinated ethylene propylene (FEP), fiberglass-reinforced epoxy (FRE), and fiberglass-reinforced plastic (FRP).

For anyone not familiar with these materials, ABS is a thermoplastic material like PVC and is a terpolymer of acrylonitrile, butadiene, and styrene. A wide range of properties can be achieved by varying the ratio of these monomers and by using additives (Sax and Lewis 1987). FEP is a fluoropolymer and is a copolymer of tetrafluoroethylene and hexafluoropropylene. It is similar to PTFE in its chemical and physical properties, although it has a slightly higher coefficient of friction (Sax and Lewis 1987). According to the manufacturer, FRE well casing is constructed of 75% high silica glass and 25% high purity, closed molecular epoxy. The epoxy is manufactured from bisphenol A-type epoxy resins cured with methyl tetrahydrophthalic anhydride (Cowgill 1988). Ac-

ording to the manufacturer's literature, the FRP used in this study consisted of 70% fiberglass and 30% polyester resin (by weight).

A literature review found only a few studies that dealt with sorption of organic solutes and leaching of organic constituents by these four materials. Gillham and O'Hannesin (1990) rated several polymeric materials with respect to sorption of organic solutes (Table 1). With respect to leaching of organic contaminants from FRE casing, Cowgill (1988) found that two organic contaminants leached from ground casings (diethyl phthalate and bisphenol A), but nothing leached from intact casings after three weeks' contact.

To assess the overall suitability of these four materials for use in groundwater monitoring wells, we conducted a series of studies to examine the chemical resistance of these materials (Ranney and Parker 1995), sorption of organic solutes by these materials (Ranney and Parker 1994), and leaching

Table 1. Performance ranking of polymeric well casing materials (from least affected to most affected).

Degradation by Chemicals

FEP, PTFE < FRE < FRP < PVC < ABS
Taken from Ranney and Parker (1995)

Sorption of Organic Solutes

FRE, PVC < FEP, PTFE, FRP << ABS
Taken from Ranney and Parker (1994)

Rigid PVC < FG < PF < PTFE < PE < flexible PVC

where: FG = epoxy-impregnated fiberglass

PE = polyethylene

PF = polyvinylidene fluoride

Taken from Gillham and O'Hannesin (1990)

Leaching of Organic Constituents

PVC, FEP, PTFE < FRE < FRP << ABS

Taken from Ranney and Parker (1994)

of organic constituents from these materials (Ranney and Parker 1994). In these studies, we compared these four materials with two other commonly used polymeric well casing materials, PVC and PTFE. The results from these two studies are summarized in Table 1. The results for sorption of organic solutes agree fairly well with Gillham and O'Hannesin's (1990) findings, except that they found FRE to be more sorptive of organic solutes than rigid PVC, and we did not (Ranney and Parker 1994). We believe the reason their findings differed slightly from ours is because they tested FRE tubing and PVC pipe while we tested well casings made for monitoring wells. It was decided to eliminate ABS from further consideration since our studies (Ranney and Parker 1994, 1995) had shown the ABS tested (waste and vent pipe) was not a good material for monitoring organic contaminants and because ABS well casing was no longer available.

To determine the overall suitability of FEP, FRE, and FRP for groundwater monitoring wells, it is also important to assess whether these materials sorb or leach metals. A review of the literature on sorption and leaching of metals by these products produced relatively little information.

According to Masse et al. (1981) anions do not strongly associate with polymer surfaces such as polyethylene (PE) and PTFE. Hewitt (Parker et al. 1990, Hewitt 1992) observed that PTFE and rigid PVC did not sorb the anionic forms of As and Cr. However, sorption of cations by these polymers does appear to occur (Masse et al. 1981, Parker et al. 1990, Hewitt 1992). Only one laboratory study (Raber et al. 1983) was found that specifically addressed sorption of metals by any of these three materials. Raber et al. (1983) tested twelve different polymers for sorption of three radionuclides (SeO_3^{2-} , Sr^{2+} , and Cs^+) and found that FEP and PTFE were among the least sorptive materials.

Several studies (Hewitt 1989, Parker et al. 1990, Hewitt 1992, 1994) have assessed sorption of metals by PTFE. Since FEP and PTFE are both fluoropolymers, data for PTFE may indicate how FEP will perform. These studies show that under static conditions there was relatively little sorption of several cations (Pb, Cd, Cu, Fe) by PTFE when compared with rigid PVC and especially SS casings (Parker et al. 1990, Hewitt 1992). However, under dynamic conditions, significant losses of

Table 2. Method detection limits and EPA primary drinking water quality standards (Maximum Contaminant Levels [MCLs]).

<i>Metal</i>	<i>MDL</i>	<i>MDL</i>	<i>EPA primary drinking water std.</i>	
	<i>leaching study</i>	<i>sorption study</i>	<i>1975 Interim std¹</i>	<i>1994 Std²</i>
	$\mu\text{g/L}$	$\mu\text{g/L}$	$\mu\text{g/L}$	$\mu\text{g/L}$
Ag	0.010	—	50	—
As	0.41	1.5	50	50
Ba	5.1	—	1000	2000
Be	0.084	—	—	4
Cd	0.059	0.064	10	5
Cr	0.12	0.7	50	100
Cu	0.37	—	1000	1300
Ni	0.66	—	—	100
Pb	0.35	0.89	50	15
Se	8.5	—	10	50
Zn	0.19	—	—	—

¹ Given in the Federal Register (1975).

² Given in US EPA (1994).

several cations (Cd, Pb, and Fe) occurred in some samples exposed to PTFE (and PVC) screen, although these losses were substantially less than those observed for SS screens (Hewitt 1994).

With respect to the literature on leaching of metals from FEP, FRE, or FRP, only one relevant laboratory study (Cowgill 1988) was found. Cowgill searched for 30 elements in water samples that had been exposed to a ground powder of FRE well casings. Apparently, no elements leached after 72 hours' exposure, but after three weeks, mg/L levels of B and Cl and $\mu\text{g/L}$ levels of P, Mg, and Zn were found in the leachate. These concentrations were all below the EPA's drinking water standards or else were not regulated.

Although no other studies were found for FEP and FRP, we expect that FEP may behave similarly to PTFE. Hewitt (Hewitt 1989, 1992) reported that under static conditions PTFE leached substantially less of some metals than rigid PVC and especially SS well casings. Under dynamic conditions, concentrations of several metals (Cd, Cr, Cu, Fe, Ni, Pb) in samples exposed to PTFE (and PVC) well screens did not differ from the controls (Hewitt 1994).

In this report, we will compare sorption and leaching of metal species by FEP, FRE, FRP, PTFE, and PVC. In the leaching study 11 metals (Ag, As, Ba, Be, Cd, Cr, Cu, Pb, Ni, Se, and Zn) will be sought. With the exception of Ba, all these metals are on the EPA's priority pollutant list. Also, the US EPA has established maximum contaminant levels (MCLs) in drinking water (US EPA 1994) for all these metals except Ag and Zn (Table 2). In the sorption study, these five casing materials were exposed to a solution containing a mixture of $\mu\text{g/L}$ concentrations of As, Cd, Cr, and Pb.

MATERIALS AND METHODS

Materials

Five types of 5-cm-diameter (2-in.) well casings or pipes were used in this study. For PTFE, FRP, FRE, and PVC, we used well casings manufactured specifically for groundwater monitoring. We were unable to find a manufacturer that made FEP well casings, but did find one that made "pipe for sampling groundwater." We will refer to all of these materials as casings throughout this report.

Because the thickness of the walls of the five casing materials differed, we cut rings of the casings to varying lengths (~2 cm long) so that the surface area would be constant (80 cm²). The material surface-area-to-aqueous-solution-volume ratio was 0.82 cm²/cm³. Special care was taken to prevent any contamination from grease, oil, dirt, solvent, etc. during the cutting process. The PTFE, FEP, and PVC casings were cut with a high-speed steel slotting saw (VASCO M-2). The two fiberglass materials, FRE and FRP, were cut with a high-speed steel (1076) diamond band saw. The ratio of cut surface area to total surface area was approximately 18% for PTFE and PVC, 17% for FRP, 15% for FEP, and 7% for FRE.

The ring sections were rinsed with several volumes of deionized (Millipore) water and allowed to air dry in a Class 100 clean room where all subsequent cleaning and prep work was done. Plastic gloves and nylon tweezers were used to handle the ring sections.

Polypropylene (PP) jars (125 mL) with PP screw caps were used as the sample containers. The jars, PP Eppendorf pipet tips, PP volumetric flasks with PP screw caps, nylon tweezers, PE autosampler cups, and two 4-L brown glass bottles used to hold the groundwater were acid cleaned prior to being used. The equipment was acid cleaned by soaking in a 10% v/v of redistilled nitric acid and deionized water for several days, rinsing with deionized water, soaking in deionized water for several more days, rinsing with deionized water, and air drying. A Brinkman dispensette was flushed with several volumes of 2% v/v nitric acid solution and rinsed with several volumes of deionized water. The groundwater (pH 5.7) used in this study was from a well (45 m deep) located in Hartland, Vermont.

Procedure for the leaching study

One of the ring sections was placed in a PP jar, 98 mL of groundwater was added using a calibrated Brinkman dispensette, and the jar was tight-

ly capped. The sample jars were filled randomly from one of two 4-L bottles of groundwater and were stored in the dark at room temperature. There were three replicate samples for each treatment and time, including the controls. Contact times were 1, 5, 20, and 40 days. Controls consisted of jars filled only with groundwater.

On the sampling day, the jars were opened, the ring section was removed, and 2 mL of concentrated nitric acid was added to the sample jar (giving a final pH of <1 and an acid concentration of 2% v/v). This was done because acidification to a pH of less than 1.5 has been shown to be effective in preventing losses of trace metals from natural waters and aids in recovery of sorbed metals from the vessel walls (Subramanian et al. 1978, Hewitt 1989). The jars were then recapped, swirled for 10 seconds, and left until the analyses were conducted at the end of the study.

Procedure for the sorption study

The procedure for the sorption study was similar to the leaching study except that one mL of a mixed metal spike solution containing 5 mg/L As, Cr, Pb, and 2 mg/L Cd was added to 97 mL of groundwater in a PP jar. The mixed metal spike solution was prepared from serial dilutions in deionized water of certified (Fisher Scientific Co.) metal standards (1,000 mg/L). Cd and Pb were in solution as cations, while Cr (as dichromate) and As (as arsenite or arsenate) were anions. After adding the metal spike, each jar was swirled to mix the solution, the section of casing was placed in the jar, and the jar was then tightly capped. Controls consisted of jars filled with the test solution but no casing material. Final concentrations were approximately 51 µg/L for As, Cr, and Pb and 20 µg/L for Cd. The samples were stored in the dark at room temperature. There were three replicate samples for each casing material and time, including the controls. Contact times were 1, 8, 24, and 72 hours. When a sample was taken, the jar was opened, the ring section was removed, and the remaining solution was acidified as described previously.

Analyses

Analyses were performed by Graphite Furnace Atomic Absorption (GFAA) using a Perkin-Elmer Model 5100 Atomic Absorption Spectrophotometer, with a Perkin-Elmer model 5100 Zeeman background correction module, a Perkin-Elmer model 600 graphite furnace, and a Perkin-Elmer model

AS-60 autosampler. Instrument operating procedures followed the general recommendations found in the manufacturer's analytical methods manual (Perkin-Elmer 1981). Working standards were serial dilutions prepared from a certified (Environmental Resource Associates) primary mixed metal standard (1 mg/L). A range of four standard concentrations, analyzed in duplicate, was used to calibrate the instrument for each metal. A calibration check standard for each metal was prepared from serial dilutions of a certified (Fisher Scientific Co.) metal standard (1,000 mg/L). The check standard was analyzed every ten samples. If analyses indicated that drifting from the standard curve was occurring, the instrument was recalibrated and any samples analyzed since the last check were reanalyzed. All dilutions of standards were in deionized water containing nitric acid (2% v/v).

Method Detection Limits (MDLs) (Table 2) were determined following the procedure outlined in the Federal Register (1984). All the samples were analyzed twice and means were taken. Analysis of Variance (ANOVA) tests were performed on samples that showed metal concentrations consistently higher than the established MDL. If a significant difference was detected by the ANOVA, then Fisher's Least Significant Difference (LSD) test was performed to determine which materials differed from the controls and from each other. A 95% confidence level was used in these statistical tests.

RESULTS AND DISCUSSION

Leaching study

The results for those analytes where detectable levels were observed (Ba, Cd, Cr, Cu, Pb, Ni, Zn, and Ag) are given in Tables 3a–h. In instances where one or more of the three replicate values for a given metal, material, and time were below the MDL, the MDL was used in estimating a mean value. Mean normalized concentrations were determined by dividing the mean concentration for a particular material, analyte, and time by the mean concentration of the control samples for the same analyte and time. A normalized mean concentration of 1.0 meant no sorption or leaching occurred. Table 4 shows the mean normalized concentrations for these same analytes, except for Ag. Because the concentration of Ag was often less than the detection limit, mean normalized concentrations were not determined for this metal.

Table 3. Concentration ($\mu\text{g/L}$) of metals found leaching from well casings.

Treatment	Contact time, days			
	1	5	20	40
CONTROL	27.6	56.9	18.8	38.7
CONTROL	25.6	71.5	19.0	37.9
CONTROL	29.4	28.0	21.5	31.4
\bar{X}	27.5 ^a	52.2 ^a	19.8 ^a	36.0 ^a
% RSD	7.05	42.4	7.50	11.1
PVC	49.8	73.7	17.9	35.3
PVC	55.0	75.0	10.5	29.4
PVC	48.1	94.1	48.1	51.3
\bar{X}	51.0 ^e	81.0 ^b	25.5 ^a	38.7 ^a
% RSD	7.05	14.1	78.0	29.3
PTFE	39.1	76.3	13.7	42.2
PTFE	40.1	68.3	13.9	30.5
PTFE	39.2	102	18.9	56.5
\bar{X}	39.5 ^c	82.2 ^b	15.5 ^a	43.0 ^a
% RSD	1.31	21.4	18.9	30.3
FEP	37.1	60.2	21.6	28.6
FEP	38.1	77.7	17.7	26.5
FEP	34.9	92.0	311	101
\bar{X}	36.7 ^{b,c}	76.6 ^{a,b}	117 ^a	52.0 ^a
% RSD	4.48	20.8	144	81.4
FRE	41.3	65.6	13.5	25.4
FRE	47.6	58.6	12.6	38.2
FRE	49.4	86.1	36.4	109
\bar{X}	46.1 ^d	70.1 ^{a,b}	20.8 ^a	57.6 ^a
% RSD	9.27	20.4	64.6	78.5
FRP	28.8	70.8	21.7	45.7
FRP	33.8	68.5	27.7	28.9
FRP	33.0	74.2	33.9	74.7
\bar{X}	31.9 ^{a,b}	71.1 ^{a,b}	27.8 ^a	49.8 ^a
% RSD	8.35	4.0	21.9	46.5

Values with the same letter for the same time were not significantly different.

Barium

All the samples, including the control samples, showed considerable variability from day to day and among the replicates (Table 3a). Throughout the study, the samples exposed to the casings all had slightly elevated mean normalized concentrations, although usually less than 2.0 (Table 4). After one day of exposure, concentrations in samples exposed to the PVC, PTFE, FEP, and FRE casings were significantly greater than the controls (Table 3a), with leaching greatest from the PVC and FRE casings and least from the FRP casings. Because of the sizable variability among replicates, most of the samples were not significantly different from the controls on the subsequent days (Table 3a), even though the concentrations remained consistently higher than the controls.

Table 3 (cont'd).

b. Cadmium					c. Chromium				
Treatment	Contact time, days				Treatment	Contact time, days			
	1	5	20	40		1	5	20	40
CONTROL	LD	LD	LD	LD	CONTROL	LD	LD	LD	LD
CONTROL	LD	LD	LD	LD	CONTROL	LD	LD	LD	LD
CONTROL	LD	LD	LD	LD	CONTROL	LD	LD	LD	LD
\bar{X}	<0.059	<0.059	<0.059	<0.059	\bar{X}	<0.12	<0.12	<0.12	<0.12
% RSD	—	—	—	—	% RSD	—	—	—	—
PVC	LD	0.088	0.19	0.12	PVC	0.18	LD	LD	LD
PVC	LD	0.084	0.10	0.29	PVC	0.20	LD	0.13	0.13
PVC	LD	0.088	0.14	0.36	PVC	LD	LD	0.28	LD
\bar{X}	<0.059	0.087 ^a	0.15 ^{a,b}	0.26 ^b	\bar{X}	<0.17	<0.12	<0.18	<0.12
% RSD	—	2.3	30	48	% RSD	—	—	—	—
PTFE	0.064	0.083	0.090	0.084	PTFE	0.26	LD	LD	LD
PTFE	LD	0.092	0.063	0.10	PTFE	0.26	LD	LD	LD
PTFE	LD	0.069	0.091	0.088	PTFE	LD	LD	LD	LD
\bar{X}	<0.061	0.081 ^a	0.081 ^a	0.092 ^a	\bar{X}	<0.21	<0.12	<0.12	<0.12
% RSD	—	15	20	12	% RSD	—	—	—	—
FEP	0.061	0.089	0.15	0.13	FEP	LD	LD	LD	0.23
FEP	LD	0.15	0.091	0.15	FEP	0.13	LD	LD	LD
FEP	0.098	0.18	0.079	0.26	FEP	0.21	LD	0.18	0.26
\bar{X}	<0.073	0.14 ^a	0.11 ^a	0.18 ^{a,b}	\bar{X}	<0.15	<0.12	<0.14	<0.20
% RSD	—	34	34	38	% RSD	—	—	—	—
FRE	0.23	0.28	0.16	0.21	FRE	0.70	0.55	0.25	0.91
FRE	0.15	0.18	0.31	0.28	FRE	0.46	0.17	0.15	0.41
FRE	0.24	0.23	0.37	0.20	FRE	0.89	0.28	0.46	0.20
\bar{X}	0.21 ^a	0.23 ^b	0.28 ^b	0.23 ^b	\bar{X}	0.68 ^a	0.33 ^a	0.29 ^a	0.51 ^a
% RSD	24	23	39	18	% RSD	9.0	59	54	72
FRP	0.48	0.62	0.76	0.91	FRP	1.44	0.30	0.32	0.19
FRP	0.30	0.62	0.63	0.75	FRP	0.29	0.24	0.24	0.13
FRP	0.81	0.68	0.97	0.80	FRP	0.44	0.34	0.16	0.18
\bar{X}	0.53 ^a	0.64 ^c	0.78 ^c	0.82 ^c	\bar{X}	0.72 ^a	0.29 ^a	0.24 ^a	0.17 ^a
% RSD	48	4.8	22	9.7	% RSD	87	17	33	19

LD Values less than MDL.

Values with the same letter for the same time were not significantly different.

All the values were well below the MCL of 2000 µg/L set by the US EPA for drinking water (US EPA 1994). The highest concentration found was 311 µg/L for a sample exposed to FEP; all the other samples had concentrations that were less than 110 µg/L.

Cadmium

For the control samples, concentrations of Cd were below the MDL (Table 3b). After one day of contact, only samples exposed to the two fiberglass casings had Cd concentrations above the MDL. Subsequently, samples exposed to all five casing materials had concentrations above the MDL. Generally, samples exposed to the PVC, PTFE, and FEP casings had the lowest concentrations and there was no significant difference be-

LD Values less than MDL.

Values with the same letter for the same time were not significantly different.

tween these materials. Concentrations in samples exposed to the FRP and FRE casings were significantly greater than the other three casings (days 5, 20, 40). However, concentrations in samples exposed to FRE casings were always significantly less than those in samples exposed to FRP. Mean concentrations for samples exposed to FRP ranged from 9 to 14 times control values, while for FRE they ranged from 3.6 to 4.8 times control values (Table 4).

In all cases, leached Cd concentrations remained well below the EPA's drinking water standards (US EPA 1994) of 5 µg/L. Samples exposed to FRP casings were the highest and yet these were still below 1.0 µg/L. For samples exposed to the other four casings, concentrations remained less than 0.4 µg/L.

Table 3 (cont'd). Concentration ($\mu\text{g/L}$) of metals found leaching from well casings.

d. Copper				
Treatment	Contact time, days			
	1	5	20	40
CONTROL	17.3	18.6	18.7	17.9
CONTROL	17.8	18.4	18.9	17.8
CONTROL	17.5	18.1	19.0	18.3
\bar{X}	17.5 ^a	18.4 ^a	18.9 ^a	18.0 ^a
% RSD	1.48	1.31	1.01	1.28
PVC	16.3	14.1	9.24	12.0
PVC	15.2	14.5	14.0	9.34
PVC	14.6	13.5	12.2	15.2
\bar{X}	15.4 ^b	14.0 ^c	11.8 ^c	12.2 ^b
% RSD	5.86	3.49	20.5	24.0
PTFE	16.6	17.7	17.8	18.0
PTFE	19.6	17.2	17.3	16.1
PTFE	15.7	17.5	20.1	19.1
\bar{X}	17.3 ^a	17.5 ^a	18.4 ^a	17.7 ^a
% RSD	11.6	1.32	8.26	8.52
FEP	15.8	15.7	16.9	14.6
FEP	15.9	15.1	16.1	14.4
FEP	16.0	15.1	14.7	13.9
\bar{X}	15.9 ^{a,b}	15.3 ^b	15.9 ^b	14.3 ^b
% RSD	0.50	2.09	7.23	2.37
FRE	8.58	9.62	8.42	5.12
FRE	10.7	11.2	9.76	8.03
FRE	10.4	10.1	8.12	9.52
\bar{X}	9.90 ^d	10.3 ^d	8.77 ^d	7.56 ^c
% RSD	11.6	7.95	9.92	29.6
FRP	13.5	11.1	11.4	8.92
FRP	12.3	10.4	9.38	8.48
FRP	13.2	12.5	10.1	8.82
\bar{X}	13.0 ^c	11.3 ^d	10.3 ^{c,d}	8.74 ^c
% RSD	5.08	9.44	10.1	2.63

Values with the same letter for the same time were not significantly different.

The results from this study can be compared with the results from a similar study (Hewitt 1989) that was concerned with metals leaching from PVC, PTFE, and SS 304 and 316 casings. In that study, Cd levels were highest in samples exposed to the 316 SS. At the beginning of the study (days 1 and 5), the mean concentration of Cd in the samples that were exposed to FRP casings was approximately half the mean concentration Hewitt observed leaching from samples exposed to the 316 SS. However, these high mean values for the 316 SS were primarily due to the presence of one high value among the replicates. Later in the study (days 20 and 40), concentrations of samples exposed to the 316 SS were consistently lower than the mean concentration of samples exposed to FRP.

e. Lead				
Treatment	Contact time, days			
	1	5	20	40
CONTROL	LD	LD	LD	LD
CONTROL	LD	LD	LD	LD
CONTROL	LD	LD	LD	LD
\bar{X}	<0.35	<0.35	<0.35	<0.35
% RSD	—	—	—	—
PVC	0.39	LD	0.36	LD
PVC	LD	LD	0.74	0.44
PVC	LD	LD	LD	0.48
\bar{X}	<0.36	<0.35	<0.48	<0.42
% RSD	—	—	—	—
PTFE	1.6	LD	0.59	LD
PTFE	0.50	0.37	0.41	0.39
PTFE	LD	LD	0.62	LD
\bar{X}	<0.82	<0.36	0.54 ^a	<0.36
% RSD	—	—	20	—
FEP	1.8	LD	0.46	LD
FEP	0.41	LD	0.52	LD
FEP	0.36	0.46	0.87	0.37
\bar{X}	0.85 ^a	<0.39	0.62 ^a	<0.36
% RSD	95	—	35	—
FRE	LD	LD	LD	LD
FRE	LD	LD	0.35	0.38
FRE	0.57	LD	LD	LD
\bar{X}	<0.43	<0.35	<0.35	<0.36
% RSD	—	—	—	—
FRP	20	9.4	8.5	11
FRP	8.7	15	7.1	5.5
FRP	6.0	6.7	7.8	13
\bar{X}	12 ^b	10	7.8 ^b	9.8
% RSD	66	39.4	8.8	40

LD Values less than MDL.

Values with the same letter for the same time were not significantly different.

Chromium

For the control samples, concentrations of Cr were all below the MDL (Table 3c). Concentrations of Cr in samples exposed to PVC, PTFE, and FEP were also generally below the MDL. Only samples exposed to FRE and FRP casings leached concentrations of Cr that were consistently above the MDL. However, there was no significant difference between the Cr concentrations of samples exposed to these two materials.

The highest concentration observed in any one sample was 1.44 $\mu\text{g/L}$ (for a sample exposed to FRP); the remainder of the samples had concentrations that were less than 1.0 $\mu\text{g/L}$. These concentrations were all well below the MCL (100 $\mu\text{g/L}$) set by the US EPA (1994) for drinking water.

Table 3 (cont'd).

f. Nickel					g. Zinc				
Treatment	Contact time, days				Treatment	Contact time, days			
	1	5	20	40		1	5	20	40
CONTROL	LD	0.72	LD	0.99	CONTROL	3.33	3.40	5.38	5.00
CONTROL	LD	LD	LD	1.14	CONTROL	3.41	3.42	5.45	5.23
CONTROL	LD	0.87	LD	0.97	CONTROL	3.42	3.49	5.22	5.33
\bar{X}	<0.66	<0.75	<0.66	1.03 ^a	\bar{X}	3.39 ^a	3.44 ^a	5.35 ^a	5.18 ^a
% RSD	—	—	—	8.74	% RSD	1.47	1.45	2.24	3.28
PVC	0.71	0.93	0.91	1.16	PVC	8.41	14.0	18.0	11.0
PVC	LD	0.77	0.69	1.69	PVC	6.51	11.2	11.0	21.0
PVC	0.83	0.99	0.96	1.33	PVC	7.48	10.7	16.6	18.1
\bar{X}	<0.73	0.90 ^a	0.85 ^a	1.39 ^{a,b}	\bar{X}	7.46 ^b	12.0 ^c	15.2 ^c	16.7 ^b
% RSD	—	12.2	16.5	19.4	% RSD	12.7	15.0	24.2	31.1
PTFE	0.78	0.90	0.82	1.17	PTFE	6.30	5.36	12.1	10.0
PTFE	1.08	1.13	0.67	1.14	PTFE	8.51	7.02	8.48	9.73
PTFE	0.71	1.08	0.96	1.13	PTFE	5.07	5.59	14.2	10.5
\bar{X}	0.86 ^a	1.04 ^a	0.82 ^a	1.15 ^a	\bar{X}	6.63 ^b	5.99 ^b	11.6 ^{b,c}	10.1 ^a
% RSD	23.3	11.5	18.3	1.74	% RSD	26.2	15.0	24.9	3.67
FEP	0.86	1.01	0.56	1.38	FEP	5.65	7.86	9.03	7.84
FEP	1.61	1.05	1.03	1.45	FEP	5.26	5.49	10.5	8.79
FEP	1.12	1.34	1.05	2.32	FEP	7.20	7.41	7.39	8.79
\bar{X}	1.20 ^{a,b}	1.13 ^a	0.88 ^a	1.72 ^{b,c}	\bar{X}	6.03 ^b	6.92 ^b	8.98 ^{a,b}	8.48 ^a
% RSD	31.7	15.9	31.8	30.2	% RSD	17.1	18.2	17.5	6.49
FRE	1.32	1.62	1.24	2.31	FRE	8.57	10.7	11.4	17.8
FRE	2.23	1.58	1.17	2.27	FRE	7.38	12.2	12.6	19.7
FRE	2.36	1.75	2.09	1.81	FRE	7.89	10.6	12.6	10.5
\bar{X}	1.97 ^{b,c}	1.65 ^b	1.50 ^b	2.13 ^c	\bar{X}	7.94 ^b	11.2 ^c	12.2 ^{b,c}	16.0 ^b
% RSD	28.9	5.45	34.0	13.2	% RSD	7.56	7.80	5.50	30.5
FRP	2.83	2.29	2.12	1.92	FRP	22.3	39.5	36.1	44.7
FRP	1.62	1.72	1.67	2.49	FRP	25.2	38.4	37.0	44.1
FRP	2.38	2.29	1.74	2.13	FRP	22.2	40.9	44.7	43.3
\bar{X}	2.28 ^c	2.10 ^c	1.84 ^b	2.18 ^c	\bar{X}	23.2 ^c	39.6 ^d	39.3 ^d	44.0 ^c
% RSD	26.8	15.7	13.0	13.3	% RSD	7.32	3.21	12.1	1.23

LD Values less than MDL.

Values with the same letter for the same time were not significantly different.

Values with the same letter for the same time were not significantly different.

Even though leached concentrations were highest in samples exposed to FRE and FRP, these concentrations were generally well below levels Hewitt (1989) observed leaching from SS 304 and 316 casings and screens under similar conditions.

Copper

The initial Cu concentration of the groundwater used in this study was approximately 18 µg/L (Table 3d). Table 4 clearly shows that none of the materials leached Cu but rather, with the exception of PTFE, sorbed significant quantities. It was surprising that FEP sorbed 10 to 20% of the copper while PTFE did not, since we expected the two fluoropolymers to perform similarly. The two fiberglass materials showed the greatest sorption

of Cu, with ~50% loss by the end of the study. In comparison, losses by the end of the study were 32% for PVC and 20% for FEP.

In a similar study, Hewitt (1989) found SS 316 casings leached significant quantities of copper; mean concentrations of leached Cu were 3 to 8 times background values.

Lead

For the control samples, lead concentrations were all less than the MDL (Table 3e). Only samples exposed to the FRP casings consistently had Pb concentrations above the MDL. Normalized concentrations for samples exposed to FRP ranged from 22 to 34 times control values (Table 4). In several samples, concentrations approached or ex-

Table 3 (cont'd). Concentration ($\mu\text{g/L}$) of metals found leaching from well casings.

h. Silver				
<i>Treatment</i>	<i>Contact time, days</i>			
	1	5	20	40
CONTROL	LD	0.047	0.019	LD
CONTROL	0.011	LD	0.064	LD
CONTROL	LD	LD	LD	LD
\bar{X}	<0.010	<0.022	<0.031	<0.010
% RSD	—	—	—	—
PVC	0.015	LD	LD	
PVC	0.028	0.019	LD	0.048
PVC	LD	LD	0.028	0.021
\bar{X}	<0.018	<0.013	<0.016	<0.026
% RSD	—	—	—	—
PTFE	LD	LD	LD	0.043
PTFE	LD	0.010	LD	LD
PTFE	LD	LD	0.059	LD
\bar{X}	<0.010	<0.010	<0.026	<0.021
% RSD	—	—	—	—
FEP	0.040	LD	0.014	0.033
FEP	LD	LD	LD	0.079
FEP	0.051	LD	LD	LD
\bar{X}	<0.034	<0.010	<0.011	<0.041
% RSD	—	—	—	—
FRE	0.040	0.031	LD	LD
FRE	LD	LD	LD	0.025
FRE	0.037	LD	0.060	LD
\bar{X}	<0.029	<0.017	<0.027	<0.015
% RSD	—	—	—	—
FRP	LD	LD	LD	LD
FRP	LD	0.050	0.018	LD
FRP	LD	LD	LD	LD
\bar{X}	<0.010	<0.023	<0.013	<0.010
% RSD	—	—	—	—

LD Values less than MDL.

ceeded the MCL of 15 $\mu\text{g/L}$ set by the US EPA (1994) for drinking water, although the mean values for each day and material were below this limit. For samples exposed to the other materials, concentrations were well below the MCL. Concentrations were always less than 2 $\mu\text{g/L}$ and generally were less than 1 $\mu\text{g/L}$.

Lead concentrations in the samples exposed to FRP were much higher than Hewitt (1989) observed for samples exposed to SS 304 and 316 under similar conditions. The other materials (PVC, PTFE, FEP, and FRP) appear to leach less lead than SS 304 and 316 casings did under similar conditions.

Nickel

Concentrations of Ni in the control samples were below the MDL, except for the 40-day sam-

Table 4. Mean normalized concentrations of metals leaching from well casings.*

<i>Treatment</i>	<i>Contact time, days</i>			
	1	5	20	40
BARIUM				
PVC	1.85	1.55	1.29	1.08
PTFE	1.44	1.57	0.78	1.20
FEP	1.33	1.47	5.90	1.44
FRE	1.68	1.34	1.05	1.60
FRP	1.16	1.36	1.41	1.38
CADMIUM				
PVC	≈ 1.0	>1.5	>2.5	>4.4
PTFE	≈ 1.0	>1.4	>1.4	>1.6
FEP	≈ 1.2	>2.4	>1.9	>3.0
FRE	>3.6	>3.9	>4.8	>3.9
FRP	>9.0	>11	>13	>14
CHROMIUM				
PVC	≈ 1.4	≈ 1.0	≈ 1.5	≈ 1.0
PTFE	≈ 1.8	≈ 1.0	≈ 1.0	≈ 1.0
FEP	≈ 1.2	≈ 1.0	≈ 1.2	≈ 1.7
FRE	>5.7	>2.8	>2.4	>4.3
FRP	>6.0	>2.4	>2.0	>1.4
COPPER				
PVC	0.88	0.76	0.63	0.68
PTFE	0.99	0.95	0.97	0.98
FEP	0.91	0.83	0.84	0.80
FRE	0.56	0.56	0.46	0.42
FRP	0.74	0.62	0.55	0.49
LEAD				
PVC	≈ 1.0	≈ 1.0	≈ 1.4	≈ 1.2
PTFE	≈ 2.3	≈ 1.0	>1.5	≈ 1.0
FEP	>2.4	≈ 1.1	>1.8	≈ 1.0
FRE	≈ 1.2	≈ 1.0	≈ 1.0	≈ 1.0
FRP	>34	>29	>22	>28
NICKEL				
PVC	≈ 1.1	>1.2	>1.3	1.4
PTFE	>1.3	>1.4	>1.2	1.1
FEP	>1.8	>1.5	>1.3	1.7
FRE	>3.0	>2.2	>2.3	2.1
FRP	>3.4	>2.8	>2.7	2.1
ZINC				
PVC	2.2	3.48	2.84	3.22
PTFE	1.96	1.74	2.17	1.94
FEP	1.78	2.01	1.68	1.63
FRE	2.35	3.24	2.28	3.08
FRP	6.86	11.5	7.34	8.48

* The mean normalized concentration was determined by dividing the mean concentration of a given analyte at a given time and for a particular casing material by the mean concentration (for the same analyte) of the control sample taken at the same time.

The mean normalized concentrations for samples where one or more values for the controls were less than the MDL are marked with >.

In cases where one or more values for the sample are also less than the MDL, the mean normalized concentration is marked with \approx .

ples (Table 3f). Thus, statistical comparisons with the control samples could be made only for the 40-day samples. Throughout the study, there was no significant difference between the concentra-

tions of samples exposed to PVC, PTFE, or FEP casings. However, after 40 days' exposure, concentrations of samples exposed to FEP casings were significantly higher than the controls. Generally, concentrations of Ni in samples exposed to the two fiberglass materials were significantly greater than the other three materials. Mean normalized concentrations for samples exposed to these two materials ranged from approximately 2 to 3.5 times the control values (Table 4). However, these elevated Ni levels may be the result of an experimental artifact rather than constituents leaching from the casing material. Nickel electroplate was used to bind the diamonds to the steel band that was used to cut these two materials. The other materials were cut with a steel slotting saw, which did not have diamonds bonded to it.

Even for the samples with the highest concentrations of Ni, leached concentrations were less than 3 µg/L, well below the MCL of 100 µg/L set by the EPA for drinking water (US EPA 1994).

No comparison can be made with the SS casings, because Hewitt's (1989) study, which was conducted under similar conditions, did not test for Ni. Under anoxic conditions, however, Hewitt (1992) found that SS 304 and 316 casings leached consistently higher concentrations of Ni than any of the casings we tested in this study. Means for samples exposed to SS 316 were the highest and were 4 to 5 times higher than the concentrations of samples exposed to the fiberglass casings.

Zinc

After one day of exposure, all the samples exposed to the well casings had significantly higher concentrations of Zn than the control samples (Table 3g, Table 4). Concentrations in samples exposed to the FRP casings were significantly higher than those in samples exposed to the other casings; mean normalized concentrations were approximately 7 to 12 times control values. Leached concentrations cannot be compared with any MCL standard for Zn because the US EPA has not set one. Also, no comparisons can be made with the SS casings because there are no data available.

Arsenic, beryllium, selenium, and silver

Concentrations of As, Be, and Se were all below the MDL. The majority of the values for Ag were also below the MDL, and do not show any apparent pattern or trend (Table 3h). In all cases, leached concentrations of Ag were less than 0.80

µg/L. Currently, the EPA has not set an MCL for silver in drinking water. However, a previous MCL value given in the EPA's Interim Primary Drinking Water Standards (Federal Register 1975) was 50 µg/L, and the values observed in this study are well below this value. Again, there are no data available for these four analytes that would allow comparisons to be made with SS casings.

SORPTION STUDY

Initial concentrations were 51 µg/L for As, Cr, and Pb and 20 µg/L for Cd.

Anions

Arsenic

There was no significant loss of As in any of the samples exposed to the casing materials (Table 5, Table A1). Since arsenic exists as negatively charged arsenates or arsenites under the oxidizing to slightly reducing conditions found in natural waters (Fowler et al. 1979), these results agree with several previous studies (Masse et al. 1981, Parker et al. 1990, Hewitt 1992) that have shown that anions do not strongly associate with polymeric surfaces. In comparison, data from

Table 5. Mean normalized concentrations of As, Cd, Cr, and Pb sorbed by well casings.

Treatment	Contact time, hours			
	1	8	24	72
ARSENIC				
PVC	1.02	1.01	1.01	1.00
PTFE	0.99	1.01	1.00	0.99
FEP	0.99	1.00	1.01	1.00
FRE	0.99	0.99	0.99	0.99
FRP	1.01	1.00	1.00	1.00
CADMIUM				
PVC	0.93	0.87	0.83	0.79
PTFE	0.97	0.95	0.93	0.99
FEP	0.98	0.96	0.95	0.98
FRE	0.95	0.91	0.89	0.94
FRP	0.96	0.96	0.90	0.94
CHROMIUM				
PVC	1.01	1.01	1.00	0.99
PTFE	1.00	1.00	1.00	0.99
FEP	1.00	1.00	1.01	1.00
FRE	0.95	0.98	0.99	0.98
FRP	1.01	1.03	1.00	1.00
LEAD				
PVC	0.90	0.70	0.61	0.56
PTFE	0.98	0.95	0.94	0.93
FEP	0.97	0.95	0.93	0.93
FRE	0.89	0.65	0.55	0.45
FRP	0.91	0.71	0.59	0.52

a study that tested types 304 and 316 SS casings showed that these casings were slightly sorptive (e.g., 10% loss in 24 hours) under similar conditions (Parker et al. 1990).

Chromium

Because Cr was added to the groundwater as dichromate, a negatively charged species, we would expect the results for this anion to be similar to those for As. Statistical analyses of these data indicated that losses due to sorption were not significant for any of the casing materials, except for a few of the samples exposed to the FRE casings (Table A2). However, these losses were slight: less than 5% (Table 5).

In similar studies that examined sorption of Cr by SS 304 and 316 casings, there was some slow sorption by SS 316 casings (e.g., 13% in eight hours) (Parker et al. 1990).

Cations

Cadmium

While the polymeric casings did not tend to sorb anions, this was not the case for cations. FEP was the only polymeric material of the five tested that had no significant effect on Cd concentrations. PVC was the most sorptive material tested—losses ranged from 7 to 21% (Table 5), and these losses were significant for all four sampling times (Table A3). Also, losses of Cd became significant after eight hours for samples exposed to FRE (9% loss) and after 24 hours for samples exposed to FRP (10% loss). Cd concentrations were also significantly lower in samples that were exposed to the PTFE casings after eight and 24 hours (~5 to 7% loss), but not by the end of the study. There was less sorption of Cd by the PTFE, FRE, and FRP casings as the study progressed. This may be because, as the leaching study showed, these materials leach low levels of this analyte.

In a similar study, both types of SS casings (304 and 316) leached Cd and therefore no sorption was observed (Parker et al. 1990). However, under low DO conditions, SS 304 was very sorptive of Cd (losses ranged from 18% at eight hours to 60% at 72 hours) (Hewitt 1992).

Lead

Since lead also exists as a cation in solution, we would expect that some of the casing materials would sorb Pb in a fashion similar to Cd. Previous studies (Parker et al. 1990, Hewitt 1992) have

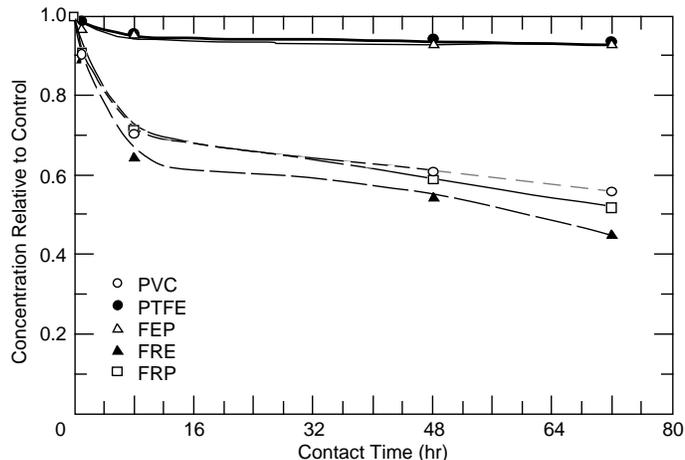


Figure 1. Sorption of lead by well casings.

shown that this analyte is readily sorbed by SS, PVC, and PTFE well casings. Table 5 and Figure 1 show that there was substantial sorption of Pb in the samples exposed to the PVC, FRE, and FRP casings. These losses were significant after one hour of exposure (Table A4). Sorption tended to be significantly greater for FRE than FRP or PVC. By the end of the study (72 hours), mean losses for these materials were 57% for FRE, 48% for FRP, and 44% for PVC. After 24 hours, concentrations of samples exposed to the fluoropolymers (FEP and PTFE) were also significantly lower than the controls, indicating that sorption had occurred. However, these losses were small (2 to 7%).

Sorption by the most sorptive material, FRE, appears to be equivalent to what has been observed under similar conditions for SS 304 and less than what has been observed for SS 316 (Parker et al. 1990). Although we do not have any explanation, sorption of Pb by PVC appears to be considerably greater in this study than what was observed in a previous study (Parker et al. 1990).

CONCLUSIONS AND RECOMMENDATIONS

These studies show that, with respect to leaching, the fiberglass materials were more apt to leach higher concentrations of contaminants than the other three materials. However, in at least one case (Ni), we suspect that this may be the result of an experimental artifact. With the exception of Cd, the performance of PVC was almost as good as the fluoropolymers. The concentrations of leached contaminants were relatively low and did not approach limits set by the US EPA for drinking wa-

ter, except for the FRP casings that leached Pb. Comparisons of these data with a similar study conducted by our laboratory (Hewitt 1989) indicated that FRE, PVC, PTFE, and FEP tended to leach less than SS 304 and 316 casings, while this was not always the case for FRP, especially for Cd and Pb.

It is possible that FRE and FRP casings would leach less under dynamic conditions. Previous studies by Hewitt (1989, 1992, 1994) have shown that PVC leached Cr and Pb under static conditions, but did not do so under dynamic conditions. In addition, several older studies (Packham 1971a,b; Gross et al. 1974; Dietz et al. 1977) have shown the leaching of metal stabilizers from PVC pipe appears to be due to a surface phenomenon, i.e., concentrations of leached metal stabilizers are highest initially, drop off with additional flushing with water, and then level off.

With respect to sorption, none of the five materials sorbed the anions tested, As and Cr. However, all five materials sorbed the cations tested (Cu, Cd, Pb), although the two fluoropolymers were the least active. With respect to sorption of Cd, PVC was the most active while FRE and FRP were more sorptive of Pb and Cu (with FRE being slightly more sorptive). Again, we might expect that these effects would be mitigated in a well where the water is replenished and sites for sorption become less available with time. However, Hewitt (1994) found that PVC and PTFE well screens continued to sorb cations under dynamic conditions. A comparison of our results with a similar study of sorption of metals by SS casings (Parker et al. 1990) also indicates that SS materials are much more sorptive than the polymeric materials we tested.

Based on our findings in this study, we would tentatively rank these materials' impact on metal concentrations as follows:

FEP, PTFE < PVC < FRE < FRP.

Based on our findings and those of others (Hewitt 1989, 1992, 1994, Parker et al. 1990), we would also rank the impact on metal concentrations of four of these materials and SS as

FEP, PTFE < PVC < FRE < SS.

Selecting well casings for a particular well is highly dependent upon a number of factors including the size and depth of the well (i.e., strength considerations), the contaminants of interest, and characteristics of the well water that might cause

Table 6. Other factors affecting well casing selection for monitoring wells.

Strength Considerations

(Going from shallowest well to deepest well)

PTFE (~FEP) << PVC, FRP < FRE < SS

Based on manufacturer information and information in Nielsen and Schalla (1991). FEP was assumed to be fairly equivalent to PTFE because no strength data were found.

Corrosion of Stainless Steel

pH < 7.0

DO > 2 ppm

H₂S ≥ 1 ppm

Total Dissolved Solids > 1000 ppm

CO₂ > 50 ppm

Cl⁻ > 500 ppm

Taken from Aller et al. (1989), Driscoll (1986).

Softening of Plastics by Organic Solutes

Most non-fluoropolymers such as PVC, FRP, FRE, and ABS can also be degraded by very high concentrations of some organic solvents. In order for this to happen:

the organic solvent must be a good solvent of the polymer and

the solvent must be present in concentrations that exceed 0.1 times the chemical's aqueous solubility.

As an example, methylene chloride is a good solvent of PVC. It must be present at a concentration that exceeds (0.1) × (~1900 mg/L), or ~190 mg/L.

References: Berens (1985), Vonk (1985, 1986), Parker et al. (1992), Parker and Ranney (1994b, 1995).

Cost of Casing Materials

PVC < FRE < FRP < SS 304 < SS 316 < FEP, PTFE

Based on the price paid for the materials used in this study in 1993.

degradation of the casing material. Table 1 summarized most of the research studies on degradation of these polymeric materials by chemicals and the effects these polymeric casings have on organic contaminants. It should be noted that while several studies (Parker et al. 1990, Gillham and O'Hannesin 1990, Parker and Ranney 1994a) have shown that SS is relatively nonsorptive of a fairly wide range of organic solutes, Reynolds et al. (1990) have shown that it can react with highly halogenated hydrocarbons, causing their degradation. Table 6 summarizes some additional information on the strength of these materials, other conditions that cause degradation of casing materials, and cost.

This series of experiments clearly shows that, of the three new materials considered in this study (FEP, FRE, and FRP), FRE may prove quite useful in monitoring applications where either SS or PVC cannot be used, especially in deeper wells. FEP does not appear to offer any clear advantage over PTFE. When cost is also considered, PVC still re-

mains the first choice for most monitoring applications. It is our intention that this information will be used to select a casing material that will offer the best possible performance at the least possible cost.

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APPENDIX A: CONCENTRATIONS OF ANIONS AND CATIONS SORBED BY WELL CASINGS

Table A1. Concentration (µg/L) of arsenic sorbed by well casings.

<i>Treatment</i>	<i>Contact time, hours</i>			
	<i>1</i>	<i>8</i>	<i>24</i>	<i>72</i>
CONTROL	48.7	50.0	48.5	49.9
CONTROL	51.1	50.4	50.6	49.4
CONTROL	49.6	48.5	51.2	49.6
\bar{X}	49.8 ^{a,b}	49.6 ^a	50.1 ^a	49.6 ^a
% RSD	2.47	2.01	2.81	0.46
PVC	50.4	48.8	51.5	49.6
PVC	50.1	49.9	50.1	50.3
PVC	51.3	51.4	49.8	49.3
\bar{X}	50.6 ^b	50.0 ^a	50.5 ^a	49.7 ^a
%RSD	1.28	2.56	1.76	1.05
PTFE	49.4	50.2	49.7	49.3
PTFE	49.6	49.7	50.1	48.7
PTFE	49.1	50.0	50.6	49.3
\bar{X}	49.4 ^{a,b}	50.0 ^a	50.1 ^a	49.1 ^a
%RSD	0.45	0.58	0.90	0.71
FEP	49.1	49.2	50.8	49.9
FEP	49.6	50.0	52.3	49.5
FEP	49.7	49.6	48.9	49.4
\bar{X}	49.5 ^{a,b}	50.0 ^a	50.7 ^a	49.6 ^a
% RSD	0.65	0.75	3.40	0.54
FRE	49.3	49.1	50.2	49.4
FRE	49.1	48.7	50.4	47.9
FRE	49.1	49.0	48.1	49.3
\bar{X}	49.2 ^a	48.9 ^a	49.5 ^a	48.9 ^a
% RSD	0.22	0.43	2.60	1.72
FRP	51.7	48.4	49.5	49.5
FRP	49.8	49.9	50.4	50.7
FRP	50.0	50.5	50.7	48.6
\bar{X}	50.5 ^b	49.6 ^a	50.2 ^a	49.6 ^a
% RSD	2.08	2.18	1.22	2.18

Values with the same letter for the same time were not significantly different.

Table A2. Concentration (µg/L) of chromium sorbed by well casings.

<i>Treatment</i>	<i>Contact time, hours</i>			
	<i>1</i>	<i>8</i>	<i>24</i>	<i>72</i>
CONTROL	48.8	49.5	50.4	49.4
CONTROL	50.0	49.3	49.4	50.3
CONTROL	49.7	49.8	49.3	49.4
\bar{X}	49.5 ^a	49.5 ^{a,b}	49.7 ^{a,b}	49.7 ^a
% RSD	1.29	0.59	1.17	1.09
PVC	49.7	49.4	49.9	49.6
PVC	50.1	50.0	49.5	48.9
PVC	49.8	50.2	49.3	49.1
\bar{X}	49.9 ^a	49.9 ^{a,b}	49.5 ^{a,b}	49.2 ^{a,b}
% RSD	0.44	0.84	0.65	0.75
PTFE	49.7	49.1	49.5	49.4
PTFE	49.9	50.0	49.3	49.5
PTFE	49.1	49.6	50.1	49.5
\bar{X}	49.5 ^a	49.6 ^{a,b}	49.6 ^{a,b}	49.5 ^{a,b}
% RSD	0.79	0.99	0.85	0.16
FEP	49.5	48.6	50.9	50.0
FEP	49.2	49.6	50.2	49.5
FEP	50.1	50.4	49.3	50.1
\bar{X}	49.6 ^a	49.6 ^{a,b}	50.1 ^b	49.9 ^a
% RSD	0.99	1.84	1.60	0.68
FRE	47.9	48.4	49.2	49.1
FRE	46.3	48.2	49.1	48.4
FRE	47.3	49.0	48.6	49.3
\bar{X}	47.2 ^b	48.6 ^a	49.0 ^a	48.9 ^b
% RSD	1.63	0.87	0.63	0.98
FRP	51.0	50.6	50.2	49.3
FRP	49.3	53.1	48.8	50.1
FRP	49.8	49.4	50.3	49.2
\bar{X}	50.1 ^a	51.0 ^b	49.7 ^{a,b}	49.5 ^{a,b}
% RSD	1.72	3.70	1.73	0.99

Values with the same letter for the same time were not significantly different.

Table A3. Concentration ($\mu\text{g/L}$) of cadmium sorbed by well casings.

Treatment	Contact time, hours			
	1	8	24	72
CONTROL	20.4	20.0	20.3	20.4
CONTROL	20.0	19.8	19.7	20.1
CONTROL	20.0	20.1	20.1	20.2
\bar{X}	20.1a	20.0a	20.1a	20.2a
% RSD	0.94	0.85	1.45	0.74
PVC	18.6	17.2	16.3	15.3
PVC	19.5	18.0	17.0	16.5
PVC	18.2	16.8	16.6	15.9
\bar{X}	18.8b	17.3d	16.6c	15.9c
% RSD	3.46	3.29	2.22	3.65
PTFE	20.5	19.1	19.8	20.1
PTFE	19.4	19.6	17.5	19.7
PTFE	18.7	18.3	18.4	20.4
\bar{X}	19.6a,b	19.0b,c	18.6b	20.0a
% RSD	4.60	3.37	6.14	1.90
FEP	20.2	18.8	19.1	20.1
FEP	18.7	19.6	18.0	19.6
FEP	20.5	18.9	20.1	19.7
\bar{X}	19.8a,b	19.1a,b	19.1a,b	19.8a,b
% RSD	4.85	2.15	5.61	1.31
FRE	19.5	18.1	17.0	18.6
FRE	19.2	18.9	17.6	18.8
FRE	18.9	17.5	19.0	19.7
\bar{X}	19.2a,b	18.2a,b	17.9b,c	19.1b
% RSD	1.67	3.91	5.77	2.83
FRP	19.2	18.8	18.1	19.1
FRP	18.3	19.8	18.0	18.2
FRP	20.2	19.2	18.1	19.7
\bar{X}	19.3a,b	19.3a,b	18.1b	19.0b
% RSD	4.93	2.49	0.44	4.01

Values with the same letter for the same time were not significantly different.

Table A4. Concentration ($\mu\text{g/L}$) of lead sorbed by well casings.

Treatment	Contact time, hours			
	1	8	24	72
CONTROL	50.7	48.9	49.9	50.2
CONTROL	48.4	49.5	51.0	51.3
CONTROL	50.1	51.6	50.1	49.2
\bar{X}	49.7a	50.0a	50.3a	50.2a
% RSD	2.43	2.88	1.15	2.05
PVC	43.4	36.3	30.8	26.2
PVC	45.8	33.4	30.0	28.9
PVC	45.1	35.5	30.9	28.7
\bar{X}	44.8b	35.1b,c	30.6c	27.9c
% RSD	2.72	4.25	1.57	5.37
PTFE	48.2	48.1	45.5	46.6
PTFE	49.0	45.4	48.3	45.8
PTFE	49.0	48.8	48.7	47.2
\bar{X}	48.72a	47.5a	47.5b	46.5b
% RSD	1.01	3.81	3.66	1.59
FEP	49.9	47.7	48.0	46.8
FEP	48.2	47.9	46.9	47.2
FEP	47.2	47.5	45.0	46.2
\bar{X}	48.4a	47.7a	46.6b	46.7b
% RSD	2.87	0.36	3.24	1.03
FRE	44.6	31.6	28.6	22.0
FRE	43.8	33.3	27.7	23.4
FRE	44.2	32.9	27.4	21.9
\bar{X}	44.2b	32.6c	27.9d	22.4d
% RSD	0.95	2.70	2.18	3.71
FRP	45.8	33.4	30.1	23.8
FRP	44.4	37.7	27.2	23.8
FRP	45.0	35.1	31.8	30.2
\bar{X}	45.1b	35.4b	29.7c,d	26.0c
% RSD	1.55	6.16	7.85	14.25

Values with the same letter for the same time were not significantly different.

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13. ABSTRACT (<i>Maximum 200 words</i>) The most commonly used well casing materials (polyvinyl chloride [PVC], polytetrafluoroethylene [PTFE] and stainless steel) cannot be used for all monitoring applications. Therefore, a series of experiments was conducted to compare three alternative polymeric well casing materials (fluorinated ethylene propylene [FEP], fiberglass-reinforced epoxy [FRE] and fiberglass-reinforced plastic [FRP]) with PVC and PTFE. These studies were conducted to determine the overall suitability of these materials for use in groundwater monitoring wells. Previous studies compared these materials for sorption of dilute organic solutes, leaching of organic constituents, and resistance to degradation by chemicals, especially organic solvents. This particular study focuses on sorption and leaching of metals. This study shows that the fiberglass materials were more apt to leach metal contaminants than PVC, FEP, and PTFE. Leached concentrations, with one exception (Pb leaching from FRP), were below maximum allowable limits set by the US EPA for drinking water. With respect to sorption, none of the polymers sorbed the anions tested, but all of them sorbed the cations tested. FEP and PTFE were much less sorptive than the other materials. These results and those from our previous studies can be used, along with other considerations, to select a casing material that is best suited for the intended monitoring application and conditions in the well.					
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